The California Water Sustainability Indicators Framework

Final

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1. Executive Summary

Measuring environmental, social, and economic conditions and influences on these conditions is an important part of knowledge-building and adaptive management. The California Water Sustainability Indicators Framework (hereafter "Framework"), developed as part of the California Water Plan Update 2013, brings together water sustainability indicators that will inform us about water system conditions and their relationships to ecosystems, social systems, and economic systems. The evaluation of the selected sustainability indicators is anticipated to reveal how our actions or inaction can degrade or improve conditions that lead to water sustainability. The Framework is built around both statements of intent (e.g., objectives) and domains (e.g., water quality). Reporting indicator condition is based upon the principle of measuring how far a current condition is from a desired condition. The Framework is intended to support reporting of indicators to a wide array of water and environmental stakeholders, the public, and decision makers to build knowledge and to enhance adaptive decision-making and policy change.

The basis of the Framework is an overall vision for water sustainability for California, including an understanding of sustainability, indicators, and related terms. Based on a generally agreed-upon vision among stakeholders in a given region, in the whole state, the proposed Framework operates through a series of inter-related steps, beginning with defining sustainability goals and objectives and ending with reporting conditions relative to sustainability targets. Each step generally follows the previous step and completing all steps is necessary for a full evaluation of water sustainability. The Framework is designed to be scale-independent, so it can be applied from local to global scales. Ultimately, the Framework informs us how well we are sustaining the natural, social, and economic systems that we depend upon, at least in terms of water, and based on what we know about stresses to these systems, how we can improve degraded conditions.

1.1. Why Are We Doing This?

"California water management must be based on three foundational actions: use water efficiently to get maximum utility from existing supplies, protect water quality to safeguard public and environmental health and secure the state's water supplies for their intended purpose, and expand environmental stewardship as part of water management responsibilities."

California Water Plan Update 2009, Volume 1, page 5-20.

The mission of the California Department of Water Resources (DWR) is to manage the water systems of California, to benefit the State's people, and to protect, restore, and enhance the natural and human environments. To fulfill this mission, DWR coordinates preparation of the California Water Plan Update, Bulletin 160 (Water Plan), in collaboration with other state agencies. Providing a comprehensive statewide water reporting and management framework, the Water Plan is the State's strategic plan for developing and managing water resources statewide. Mandated by the California Water Code (Section 10005 et seq.) and updated every five years, the Water Plan sets forth a blueprint for water managers, legislators, and the public to consider options and make decisions regarding California's water future.

With a growing recognition that California's water systems are finite, and faced with climate change, growing population, and more stringent environmental requirements, decision-makers, water managers, and planners are becoming increasingly aware of the need to both sustainably manage water and respond to changing availability and constraints on water. In the Water Plan Updates 2005 and 2009, the State refocused attention on the sustainability of California's water systems and ecosystems in light of current water management practices and expected future changes. However, one recurring question from stakeholders has been, "How can we ascertain that the objectives of the Water Plan, the associated resource management strategies, and recommended actions would lead to sustainable water use and supply for the State and its various hydrologic regions?"

To respond to the above concern, one of the guiding principles established for decision-making in the California Water Plan Update 2009 was: "Determine values for economic, environmental, and social benefits, costs, and tradeoffs to base investment decisions on sustainability indicators." However, there are major impediments to address the state's water sustainability using sustainability indicators. These include: inconsistent terminologies and definitions used; absence of a systematic analytic framework and methodologies for quantification of water sustainability indicators; and a potential lack of data to undertake the appropriate analysis to assess sustainability of water resources through the development and on-going tracking of a set of sustainability indicators. As part of the Water Plan Update 2013, DWR initiated a process to develop a framework and a set of preliminary sustainability indicators. The developed framework is intended to help us identify, compute, and evaluate a set of relevant sustainability indicators that would help monitor progress towards sustainability of natural and human water systems.

1.2. Who Are We Working With?

The core team of DWR, University of California, Davis (UC Davis) and U.S. Environmental Protection Agency (USEPA) scientists has put together a stakeholder-driven, collaborative, and transparent process for reaching agreement on a water sustainability vision through work team activities, meetings, workshops, and outreach. Our intent is also to ensure that the Framework and analysis developed as part of this project have solid scientific and technical underpinnings and are defensible and well accepted by the peers in the field. We used the Water Plan's extensive stakeholder participation processes for this purpose:

- DWR and partner agencies work teams – DWR staff work with USEPA and other agency staff and UC Davis technical experts.
- Water Plan's Statewide Water Analysis Network – convene and connect with leading experts to ground-truth the technical analyses.
- Sustainable Water Resources Roundtable - Bring in the latest perspectives on the methods and practices related to water resources sustainability.
- State Agency Steering Committee - weigh in overall State government coordination and perspective in the water planning process.
- Water Plan Public Advisory Committee – access views of a broad stakeholder group.
- Regional Forums – obtain regional perspective using regional and local relationships through DWR's Region Offices, Integrated Regional Water Management (IRWM) outreach activities, and Regional Forums.
- Tribal Advisory Committee - involve the California Native American Tribes in the state and regional planning process.
- Federal Agency Network - engage federal agencies in the state water planning process.

1.3. What Do We Mean by Sustainability?

The California Water Plan Update 2009 included a vision statement laying the foundation for how California can be sustainable in water use and management. The vision is the following:

> *California has healthy watersheds and integrated, reliable, and secure water resources and management systems that: Enhance public health, safety, and quality of life in all its communities; Sustain economic growth, business vitality, and agricultural productivity; and Protect and restore California's unique biological diversity, ecological values, and cultural heritage.*

Generally speaking, "A system that is sustainable, should meet today's needs without compromising the ability of future generations to meet their own needs" (Brundtland Commission, 1983). The USEPA defines sustainability as "The satisfaction of basic economic, social, and security needs now and in the future without undermining the natural resource base and environmental quality on which life depends." The state of Minnesota adopted this definition of sustainable water use as part of their Water Sustainability Framework, "That which does not harm ecosystems, degrade water quality, or compromise the ability of future generations to meet their own needs." And there are many other definitions as well.

In order to help meet the vision of the Water Plan, we propose that sustainability be thought of in two main ways:

1) *as a goal toward which we collectively strive, recognizing the inherent value of "becoming sustainable" and*
2) *an emergent property of collectively "acting sustainably," which affects small or large parts of the natural, social, and economic systems we rely upon*.

What the above concepts mean in terms of the Framework is that we would measure our progress toward the goal of becoming sustainable by measuring how individual components of natural, social, and economic systems respond to our actions. So, sustainability indicators measure the condition of parts of the systems, and/or performance of our actions, as well as our distance from and progress toward a range of sustainability.

Definitions of relevant terms related to sustainability and indicators are provided in Table 1.

Table 1. Glossary of terms related to sustainability and indicators

Term	Definition
Objective	Objectives are measurable descriptions of desired outcomes for particular aspects of the system's condition.
Indicator	Indicators are typically qualitative or quantitative parameters that are familiar from monitoring programs (e.g., streamflow), becoming indicators when selected to represent parts of ecological, social, or economic systems.
Index	An index is an aggregation of indicators that may convey a story about a system, or part of a system.
Domain	Domains are types of category (i.e., collection of like attributes) and are terms of art referring to large parts of natural or social systems (e.g., landscape condition).
Metric	Metrics are measurable characteristics of systems and are the building blocks of indicators, and thus the foundation of condition assessment. Examples include streamflow, groundwater level, native fish population size, and water temperature.

1.4. How Does the Indicators Framework Work?

The Framework is centered around two principles:

1) *stakeholders can provide the policy and technical framing of sustainability vision, goals, and objectives necessary to choosing indicators and*
2) *indicators and reference points are the necessary tools for measuring progress toward sustainability.*

We envision the Framework as an active process of gathering information, distilling data to tell a story, learning from what is found, and adapting to improve sustainability (Figures 1 and 2). The active role of tribes and stakeholder organizations and the transparent reporting provides the social context necessary for the technical information contained in indicators to penetrate decision-making cycles.

The Framework is organized into steps corresponding to major procedural endeavors. Completing each step leads to subsequent steps and completing all steps is necessary for a full evaluation of water sustainability. A detailed representation of the Framework is depicted in Figure 2, showing the steps involved with linking sustainability goals and objectives into public policy by using reliable data and scientific information. Both the conceptual representation (Figure 1) and the detailed representation (Figure 2) of the Framework highlight the adaptive and collaborative nature of efforts to develop sustainable policies.

- **Step 1** Describe the overall vision for sustainability and define water sustainability and related terms
- **Step 2** Set water sustainability goals and objectives corresponding to the vision and describe domains (e.g., water supply)
- **Step 3** Select indicators corresponding to the goals and objectives and covering all domains; define targets for each indicator; describe potential causes of change in indicator condition
- **Step 4** Collect data for each indicator, maintain and describe data provenance; analyze data according to distance from current state to target state; measure trend in condition and significance of trend
- **Step 5** Describe summary condition and trend in condition in an online report card; evaluate performance of system sectors
- **Step 6** Evaluate causes of condition departure from target condition and individual and programmatic actions that could maintain good conditions and repair poor conditions
- **Step 7** Describe contribution of evaluation to change in scientific knowledge, policy effectiveness, and public/decision-maker education

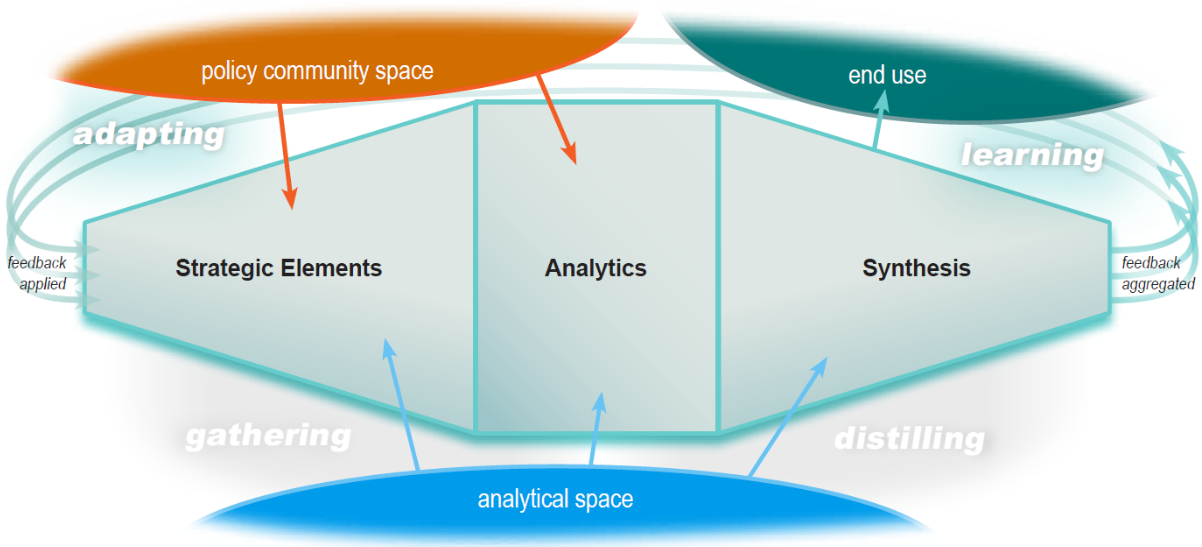


Figure 1. Conceptual representation of the Sustainability Indicators Framework

For the envisioned Framework, we use the structure of a vision- goals/objectives-indicators nested hierarchy. In the Water Plan Update 2009, there are goals, objectives, guiding principles, and resource management strategies in separate narrative tools directing actions and desired outcomes. The Framework is based upon "water sustainability goals and objectives" and can be used to evaluate whether meeting the goals, objectives, and resource management strategies of the Water Plan leads towards sustainable water use and supply in California. The water sustainability goals and objectives derive their meaning and much of their text from the Water Plan statements of intent, but attempt to make clearer connections with the idea of sustainability across ecosystem, social system, and economic system.

As shown in Figure 2, a sequence of steps begins with selecting goals and objectives (going from left to right), the selection of indicators for each objective, evaluating indicator condition relative to reference conditions, and reporting indicator conditions to inform knowledge development and policy decisions.

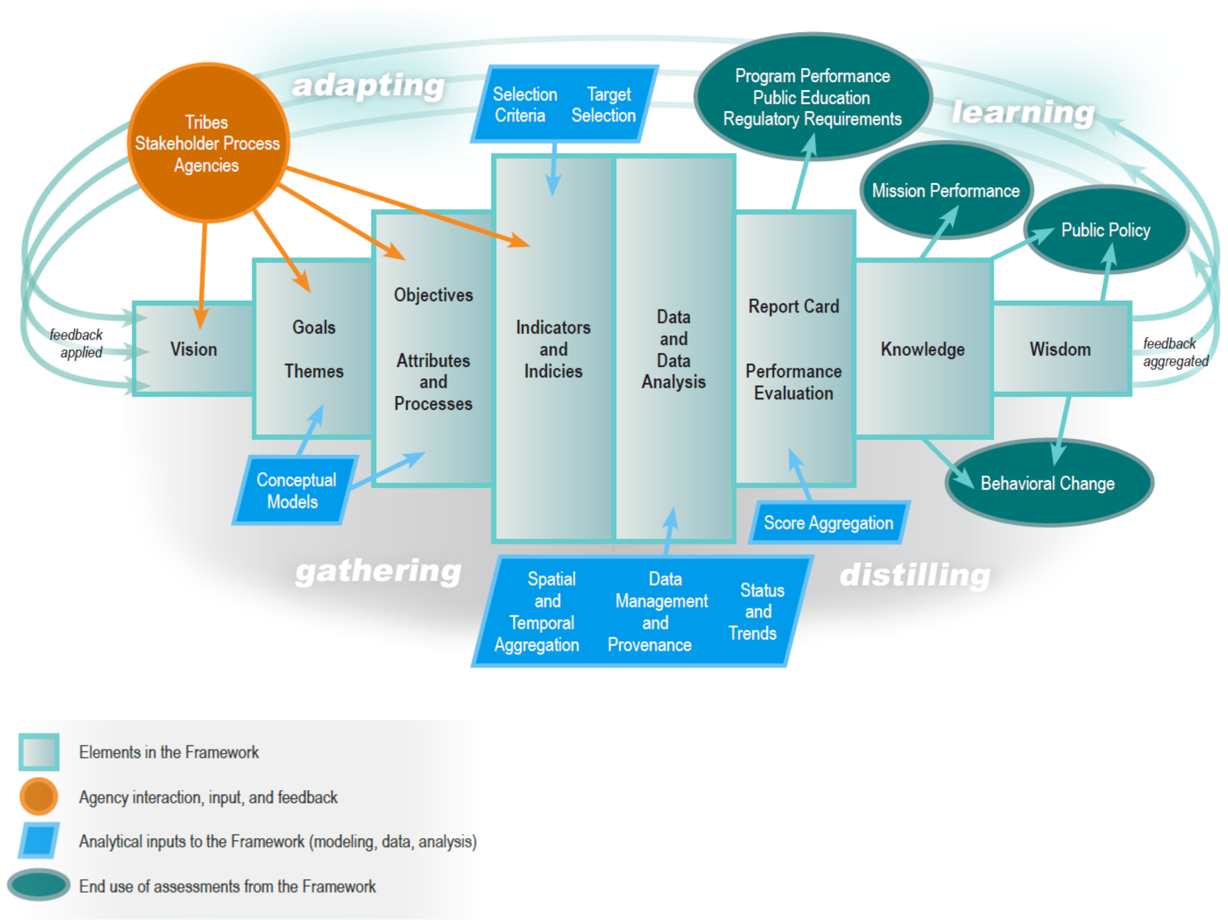


Figure 2. Diagram of the Sustainability Indicators Framework showing the steps and inputs and outputs from each step

1.5. Where Can the Framework be Used?

One anticipated utility of the Framework is that it will provide a toolbox, useful templates, and a set of illustrative examples for IRWM regions to conduct water sustainability analysis for local and regional water management. By utilizing the Framework, local and regional water and other agencies comprising the IRWM regions will be able to improve their sustainability through an evaluation of condition and trends of relevant indicators reflective of their particular needs. The process will also help identify issues and data gaps to inform future data monitoring needs on a local and regional scale to enable better quantification of water sustainability in the future. Similar to the case for the state as a whole, the indicator analysis on a local and regional scale by the IRWM regions is also expected to highlight policy needs for ensuring the local and regional water sustainability.

1.6. When Will We Finish the Framework?

A team from UC Davis, DWR, and USEPA, with input from Water Plan Advisory Committees and others involved in the Water Plan, formulated an approach that is consistent with both the best scientific practices for indicator systems and the California Water Plan. The approach is based upon previous DWR-funded projects by the UC Davis lead scientist (Shilling et al., 2010 & 2011). We acknowledge that defining and developing the Framework will be an ongoing, iterative, and evolutionary process. As we continue to receive stakeholder feedback and learn from testing the Framework at the state and region scales, we have continued to refine the Framework as part of the Water Plan Update 2013 process. The final version of the Framework (this document) is included in the Water Plan Update 2013.

1.7. How Are Indicators Connected to Ecological and Water Footprints

The basic idea of the ecological footprint is that our activities and physical infrastructure measurably affect an area or other portion of ecosystems (the "ecological footprint"). For example, the land-area required to supply an average US resident with food is about 2.4 acres. The irrigation and other water requirements for providing food and other needs can be measured as a volume of water, (the "water footprint"). In the US, the per capita water footprint is about 2,480 cubic meters or 650,000 gallons per year (Hoekstra, 2009). These approaches for measuring our effect on different attributes of natural systems rely on a combination of understanding how human endeavors occur in ecological domains and how much of an ecological attribute may be affected. Indicators are a way to measure these endeavors and ecological attributes. This provides a connection between the more traditional world of condition indicators and a comprehensive way of measuring and describing our effects on natural systems.

In Phase II of the Water Sustainability Indicators project, we have estimated California's water footprint and provided that information as an important index of human impacts to water systems. It is not intended to replace other indicators, but to serve as a composite index of multiple indicators of human uses of water and impact on natural systems. The Phase II effort of the Water Sustainability Indicators project is documented in a companion volume titled, "California Water Sustainability Indicators Framework: Assessment at State and Region Scales" and is provided at http://indicators.ucdavis.edu. The companion volume is also included as an article in the California Water Plan Update 2013, Volume 4 Reference Guide at http://www.waterplan.water.ca.gov/cwpu2013/index.cfm.

2. Approach

The California Water Sustainability Indicators Framework is composed of a cycle of process steps that build upon each other. The cycle begins with defining what is meant by sustainability and other terms and completes one cycle by informing policy and decision-making. The process is intended to be part of a cycle of adaptive learning and action. The indicators and the process of developing, analyzing, and interpreting them are not intended to be stand alone, so links are described with regional planning, ecosystem services, and the idea of a water footprint.

2.1. Process Steps

Step 1: Describe Vision for Sustainability and Define Terms

Describe the overall vision for sustainability and define water sustainability and related terms

Sustainability has many definitions. The USEPA defines sustainability as "The satisfaction of basic economic, social, and security needs now and in the future without undermining the natural resource base and environmental quality on which life depends." The state of Minnesota adopted this definition of sustainable water use as part of their Water Sustainability Framework: "That which does not harm ecosystems, degrade water quality, or compromise the ability of future generations to meet their own needs."

In order to help meet the vision of the Water Plan, we propose that sustainability be thought of in two main ways:

1) *as a goal toward which we collectively strive, recognizing the inherent value of "becoming sustainable" and*
2) *an emergent property of collectively "acting sustainable," which affect small or large parts of the natural, social, and economic systems we rely upon.*

What the above concepts mean in terms of the Framework is that we measure our progress toward the goal of becoming sustainable by measuring how individual components of natural, social, and economic systems respond to our actions. So, sustainability indicators measure the condition of parts of the systems, and/or performance of our actions, as well as our distance from and progress toward a range of sustainability goals.

Step 2: Set Water Sustainability Goals/Objectives and Domains

Set water sustainability goals and objectives corresponding to the vision and describe domains (e.g., water supply)

Society expresses its intent through a variety of mechanisms, including policies, stakeholder goals, etc. Social intent is an important organizing principle for reporting conditions and planning for sustainability. The California Water Plan vision statement expresses the overall intent of the Plan in a general way. The Water Plan process and regional water planning are also very inclusive, thus "social intent" here should be thought of as the product of a broader governance process than by single agencies or the Legislature.

Domains are term of art referring to large concepts in the environment and management, that do not necessarily contain, or imply, stated goals or objectives. For example, measuring water quality consists of measuring parameters such as dissolved oxygen, concentrations of contaminants, and water temperature. The measurements or the combination of parameters to represent water quality do not necessarily reflect a goal for water quality, such as "water should be of high enough quality to support drinking water needs and healthy aquatic ecosystems".

Water Sustainability Goals and Objectives

In the Framework, a goal is a broad statement describing where a community or society would like to end up, an objective is a more detailed and measurable aspect of broader goals and indicators are the ways that we measure achievement of objectives and progress toward goals.

Goals are often narrower expressions of intent than vision statements and describe the desired outcome of a system or set of practices. Goals are often broad statements, sometimes with several possible pathways to the outcome. The term "objectives" is often used in the same way as the term "goals"; more often objectives are intended to convey a more exact and measurable desired outcome. An example of a goal from the Water Plan Update 2009 is "Water resource and land use planners make informed and collaborative decisions and implement integrated actions to increase water supply reliability, use water more efficiently, protect water quality, improve flood protection, promote environmental stewardship, and ensure environmental justice in light of drivers of change and catastrophic events." A common structure for these systems is a vision-goals-objectives-indicators-metrics nested hierarchy (see Appendix C for global examples). The Water Plan does not have this structure. Each list of goals, objectives, guiding principles, and resource management strategies are separate narrative tools directing actions and desired outcomes.

Objectives (Water Plan Update 2009)
1. Expand integrated regional water management
2. Use and reuse water more efficiently
3. Expand conjunctive management of multiple supplies
4. Protect surface water and groundwater quality
5. Expand environmental stewardship
6. Practice integrated flood management
7. Manage a sustainable California Delta
8. Prepare prevention, response, and recovery plans
9. Reduce energy consumption of water systems and uses
10. Improve data and analysis for decision-making
11. Invest in new water technology
12. Improve tribal water and natural resources
13. Ensure equitable distribution of benefits

The Water Sustainability Indicators Framework is based upon "water sustainability goals" (Table 2). The goals were derived primarily from the language and intent expressed in the Resource Management Strategies (RMS) from the Water Plan Update 2009. The RMS were used because they provided the most detail and clearest statements of intent in the Water Plan, which aids in the development of corresponding indicators, which are in turn used to measure condition and performance of social and natural systems affected by the Plan. The Water Plan objectives are also referred to, in order to ensure consistency with the several ways that the Plan describes sustainable management of water.

Our goals and objectives for natural and human systems is one way to organize indicators. Goals and objectives are statements of social intent that give voice to specific parts of our overall vision of sustainability. Because of their relative specificity, it is possible to attach indicators to goal or objective statements and evaluate how close we are to achieving them. This evaluation is useful as an assessment of condition, as well as a decision-support tool to inform future investments of regulatory, institutional, funding, or other types of effort. In other words, if we want to know "how sustainable" we are within our various goals for the natural and social environment, we can use indicators to find out. We can use those same indicators to decide what management strategies and actions might help us to become more sustainable.

The sustainability goals can be used to evaluate progress toward meeting the principles, goals, and vision of the Water Plan. The sustainability goals derive their meaning and much of their text from the Water Plan Update 2009 statements of intent, but they make clearer connections with the idea of sustainability across environmental, economic, and equity/social considerations (the 3 E's). In the case of the Framework, "environmental" refers to natural attributes and systems, including those that people take benefit from; "economic" refers to financial and non-financial values that affect or make up economic systems; and "equity" refers to fair and even access to benefits and decision-making for all communities. Implementing the sustainability goals will depend upon interaction with impacted communities and tribes in order to ensure more equitable distribution of benefits and participation in decision-making across all goals.

Table 2. Water sustainability goals and their relationship to other elements of the Water Plan

Proposed Water Sustainability Goals	**Connection to Other Water Plan Elements**
Goal 1. Manage and make decisions about water in a way that integrates water availability, environmental conditions, and community well-being for future generations.	CWP Objectives 12,15,16
Goal 2. Improve water supply reliability to meet human needs, reduce energy demand, and restore and maintain aquatic ecosystems and processes.	CWP Objectives 2,3,7,8,9,12; RMS Reduce demand; Increase water supply
Goal 3. Improve beneficial uses and reduce impacts associated with water management.	CWP Objectives 7,13,14; RMS Operational efficiency
Goal 4. Improve quality of drinking water, irrigation water, and in-stream flows to protect human and environmental health.	CWP Objectives 4,7; RMS Water quality
Goal 5. Protect and enhance environmental conditions by improving watershed, floodplain, and aquatic condition and processes.	CWP Objectives 5,7; RMS Natural Resources
Goal 6. Integrate flood risk management with other water and land management and restoration activities.	CWP Objectives 1,6,8; RMS Improve flood
Goal 7. Employ adaptive decision-making, especially in light of uncertainties, that support integrated regional water management and flood management systems.	CWP Objective 1,10,15,16,17; various RMS

Water Sustainability Domains

People often partition information into categories (e.g., fruits, vegetables, and dairy) because it assists in communication of ideas and needs. Domains are a formal name for categories or areas of concerns, and are used in the Framework to refer to the components of the natural and artificial water system.

Water sustainability goals and objectives discussed previously are just one way to organize our thinking about an evaluation of sustainability. Another common approach is to evaluate progress within water sustainability domains (e.g., ecosystem health). Domains are used to organize indicators so that the combined scores of indicators within a domain can be used to understand specific areas of concern (e.g., water quality). Five domains of natural and human systems were defined for the Framework (Table 3), which capture most of the environmental, social, and economic concerns about water sustainability: *water supply reliability, water quality, ecosystem health, adaptive and sustainable management, and social benefits and equity*.

Because of the complexity and inter-relatedness of the water system, it is not possible to form perfect domains that do not overlap with each other. That is only a problem if indicator scores within a domain are duplicated by indicator scores in another domain and we want to add the two domains together (i.e., double-counting). An example is “water supply reliability” (Table 3), which refers to water being readily available to society to meet multiple needs. One could argue that water supply for the environment fits in this domain. That is possible, but in the Framework, water for the environment has been placed in the ecosystem health domain.

Table 3. Water sustainability domains

Sustainability Indicators Domains
WSR – Water Supply Reliability = The availability or provision of water of sufficient quantity and quality to meet water needs for health and economic well-being and functioning.
WQ – Water Quality = The chemical and physical quality of water to meet ecosystem and drinking water standards and requirements.
EH – Ecosystem Health = The condition of natural system, including terrestrial systems interacting with aquatic systems through runoff pathways.
ASM – Adaptive and Sustainable Management = A management system that can nimbly and appropriately respond to changing conditions and that is equitable and representative of the various needs for water in California.
SBE – Social Benefits and Equity = The health, economic, and equity benefits realized from a well-managed water system, including management of water withdrawal and water renewal.

Step 3: Select Indicators and Corresponding Targets

Select indicators corresponding to the goals and objectives and covering all domains; define targets for each indicator; describe potential causes of change in indicator condition

Indicators provide the connection between statements of intent (e.g., goals) and measurable aspects of natural and human systems. Because of the importance of the indicators in determining findings and basing decisions, the indicators themselves should be carefully chosen. Similarly, target or reference conditions against which to compare current conditions for each indicator should be transparently and carefully chosen.

Quantitative and Qualitative Indicator Selection

Evaluating progress toward measurable goals and objectives is the primary intent of the Framework. To carry this out, representative and practicable indicators were selected for evaluation of those over time. Explicit criteria were used to select indicators to ensure that the resulting evaluation is robust and usable in decision-making (Appendix B).

These criteria include:

- system representation;
- sensitivity to change over time;
- supports management decisions and actions;
- availability of high-quality data;
- long-term data affordability; and
- independence of indicators from one another.

One important characteristic of indicators is whether they are "leading" or "retrospective." Leading indicators tell us something about what may happen or is going to happen. For example, if our goal is improve watershed and floodplain conditions, then one way to project benefits from surface to ground-water benefits is by measuring the proportion of aquifer recharge areas that is functional and protected from development. Undeveloped recharge areas will provide future benefits to stream flows and consumptive water use. Retrospective indicators tell us about what has already happened to conditions and processes. For example, measuring river contributions to aquatic habitat and water supply needs in response to El Nino and La Nina conditions tells us about current or recent conditions.

Both "water" and "sustainability" are big concepts, meaning that there are many possible indicators for the combined concept of "water sustainability." An important component of the Water Plan Update 2013 is the development of a useful set of indicators to help find out how sustainable California is in terms of water.

There are thousands of possible indicators to choose from to describe how well systems are performing relative to sustainability goals and objectives. Developing the Water Sustainability Indicators Framework included the investigation of several dozen indicator systems from around the world (summarized in Appendix C). Candidate indicators from these global systems and from more familiar programs in California were evaluated relative to the indicator selection criteria (Appendix B). The overall goal for the indicators as a whole was to identify a set of indicators that efficiently covered the sustainability goals and the five water sustainability domains (e.g., water quality). An additional goal was to include indicators that are the most informative about conditions and changing conditions and sustainability in general. Following the above process, appropriate indicators were selected to include in the Framework from global and California programs, based on the indicator selection criteria. They are not the only possible indicators and it is possible that some or many of them are only useful in certain circumstances, or geographic regions. Even so, these indicators are a viable library of indicators for regional evaluations of condition using the Framework, for example, in IRWM planning and implementation.

The 120 proposed indicators are listed and described in Appendix D. They are organized under each of the 7 goals and alphabetically. The indicators are also published on the Sustainability Indicators Framework website: http://indicators.ucdavis.edu/.

As shown in the text box below, example indicators from the Sustainable Water Resources Roundtable (http://acwi.gov/swrr/), a 10-year old national discussion group that includes many California members, were introduced in the Water Plan Update 2009. Although this list does not show exactly how one would measure each of these indicators, it also provides a synopsis of some possible indicators to understand water sustainability.

Sustainable Water Resources Roundtable: Recommended Indicators

- 1. Water availability. People and ecosystems need sufficient quantities of water to support the benefits, services, and functions they provide. These indicator categories refer to the total amount of water available to be allocated for human and ecosystem uses
- Renewable water resources. Measures of the amount of water provided over time by precipitation in a region and surface and groundwater flowing into the region from precipitation elsewhere.
- Water in the environment. Measures of the amount of water remaining in the environment after withdrawals for human use.
- Water use sustainability. Measures of the degree to which water use meets current needs while protecting ecosystems and the interests of future generations. This could include the ratio of water withdrawn to renewable supply.
- 2. Water quality. People and ecosystems need water of sufficient quality to support the benefits, services, and functions they provide. This indicator category is for composite measures of the suitability of water quality for human and ecosystem uses.
- Quality of water for human uses. Measures of the quality of water used for drinking, recreation, industry, and agriculture.
- Quality of water for the environment. Measures of the quality of water supporting flora and fauna and related ecosystem processes.
- Water quality sustainability. Composite measures of the degree to which water quality satisfies human and ecosystem needs.
- 3. Human uses and health. People benefit from the use of water and water-dependent resources, and their health may be affected by environmental conditions.
- Withdrawal and use of water. Measures of the amount of water withdrawn from the environment and the uses to which it is put.
- Human uses of water in the environment. Measures of the extent to which people use water resources for waste assimilation, transportation, and recreation.
- Water-dependent resource use. Measures of the extent to which people use resources like fish and shellfish that depend on water resources.
- Human health. Measures of the extent to which human health may be affected by the use of water and related resources.
- 4. Environmental health. People use land, water and water-dependent resources in ways that affect the conditions of ecosystems.
- Indices of biological condition. Measures of the health of ecosystems.
- Amounts and quality of living resources. Measures of the productivity of ecosystems.
- 5. Infrastructure and institutions. The infrastructure and institutions that communities build enable the sustainable use of land, water, and water-dependent resources.
- Capacity and reliability of infrastructure. Measures of the capacity and reliability of infrastructure to meet human and ecosystem needs.
- Efficacy of institutions. Measures of the efficacy of legal and institutional frameworks in managing water and related resources sustainably.

CWP 2009, Vol. 1, pg 5-19

Qualitative indicators are important ways of describing condition and changing condition and assessing sustainability. This type of indicator is not typically included in indicator frameworks, potentially because of the perception that measuring condition or change in this way is too inexact and data acquisition too challenging. However, there are both indicators and methods for data collection that could contribute to understanding water sustainability using this approach.

Examples of qualitative indicators relevant to water sustainability include: "Historic amounts and availability of anadromous fish"; "Historic flooding conditions (extent and timing)"; "Historic fire conditions"; "Historic availability of clean drinking water from surface or ground sources"; "Community satisfaction/happiness"; "Equitable access to decision-making."

Collecting data for these indicators can be based on surveying methods, meaning talking to select groups or randomly-selected groups of people about what conditions they observe and have observed over time. Another way would be to review historic written accounts of conditions before and during modification of different systems, such as in newspapers, journals, and technical papers. Understanding the use of these methods is important in developing cost estimates for collecting data for selected indicators. One approach that would be useful is to interview tribal elders about conditions that they recall and how those conditions have changed over time. A similar approach could also be used for non-tribal elders. Interviewing typically requires a one-on-one interaction between the subject of the interview and a facilitating interviewer. For the interview to be meaningful, several criteria need to be met: trust between the parties, an understanding of the interviewer of the culture and situation of the interviewee, and support for the time investment by both parties. Using this information to inform indicators requires coding and otherwise interpreting the interview material to inform the assessment of sustainability. Another approach that could be useful is to survey traditional or other experts using structured questionnaires. In this case, criteria relating trust and support may still be important. The output from this approach is quantification of qualitative responses about conditions and changing condition.

Select and Define Indicator Targets in Open Process

Comparing indicator condition against reference values, or targets, is a critical requirement for using indicators to inform condition assessments. These targets could be changed in future assessments, with corresponding corrections of past scores. A critical aspect of defining targets is that it should be carried out in an open and inclusive process. These targets could be based on historical conditions, desired future conditions, legal thresholds, current or anticipated physical limits, or some other value. Targets provide the context for interpreting indicator results — a number against which current status and trends can be compared. For instance, a high water temperature or an increasing trend in water temperature only tells us something meaningful about the risk of this condition to cold-water fish if we know at what temperature fish will be adversely affected, and whether the current trend is moving closer to or further away from that temperature threshold. For salmonids, temperatures above 17^{o}C begin to affect growth and survival, so one way to address water temperature is through its effect on salmonid survival (Figure 3). This means that any surface water temperature in streams bearing salmonids, and other cold-water fish, can be converted into an equivalent sustainability score, based on the idea that a management goal is the growth and survival of salmonids (Figure 3).

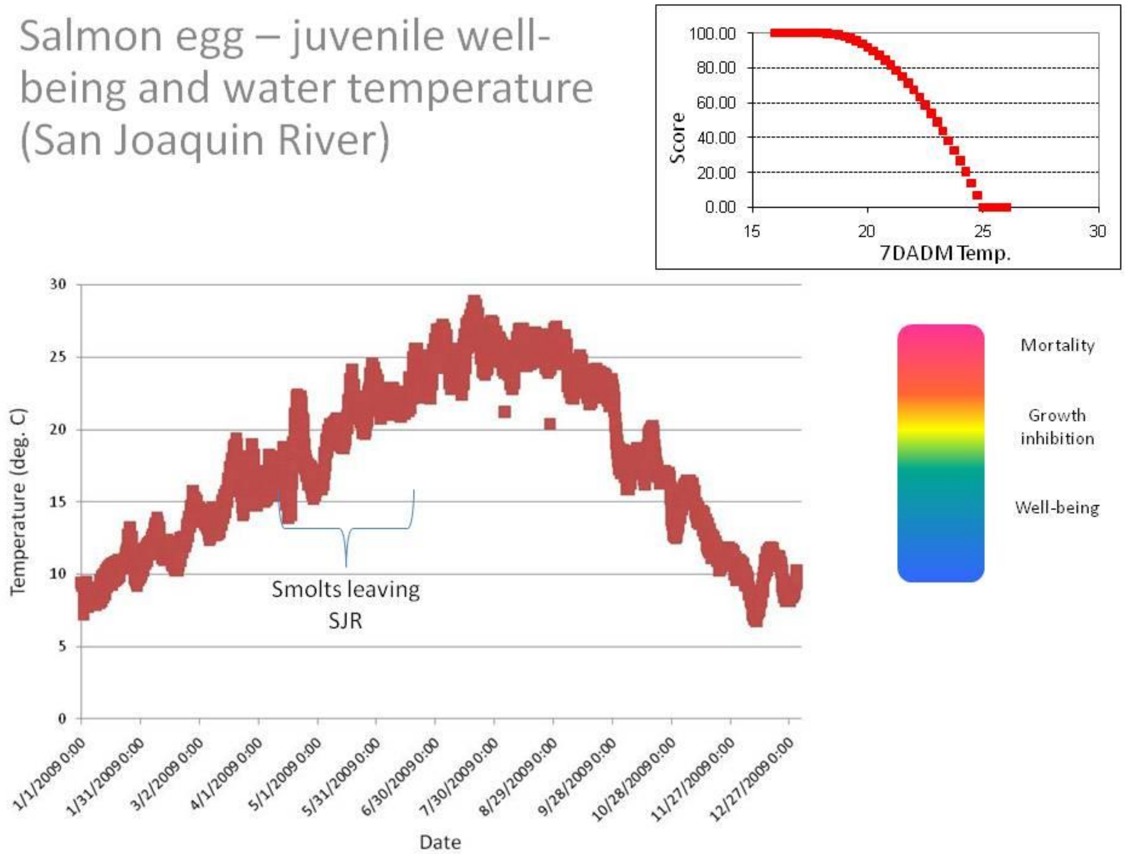


Figure 3. Comparison of salmonid young well-being to San Joaquin River water temperature. Inset graph: relationship between temperature and score for water temperature, based upon temperature sensitivity of salmonid young.

A reference value is a quantity/value of an indicator that reflects some legal or physical threshold, desired goal or target, or historic and/or pristine condition, according to what is most meaningful for the assessment and reporting purpose, and supported by science. The selection of reference values is as important as the selection of the indicator itself because, without this threshold, it is difficult to assess the magnitude of change objectively, whether the magnitude of change is important, or if any efforts at improving conditions are succeeding (National Research Council, 2000).

Step 4: Describe Data Provenance and Analyze Data

Collect data for each indicator, maintain and describe data provenance; analyze data according to distance from current state to target state; measure trend in condition and significance of trend

This step is the data collection, data management, and data analysis step in the Framework.

Indicator Data

Most indicators are chosen because information is available or is likely to become available to inform evaluation. Quantitative indicators are typically parameters that are familiar from monitoring programs (e.g., number of spawning salmon) that become indicators when they are chosen to represent important parts of social-economic-ecological systems. Because of the special role that indicators play in public education and decision-making, data sources should be carefully tracked and their provenance recorded through the indicator framework process. Data provenance refers to the described pathway that data for each selected indicator takes to become meaning as part of indicator evaluation, including where the data came from, how they might have been transformed, and what was found out.

This provenance pathway continues seamlessly with data analysis and reporting, which can be organized using the scientific workflow technique (Appendix E). Scientific workflows offer both a theoretical as well as a practical way for building a comprehensive environment for data management, analysis, and decision support. Scientific workflows combine scientific data and process workflows, and provide a graphical interface to manage the pipeline of steps of a scientific problem (Ludäscher et al 2009). One can think of scientific workflows as similar to a flowchart, where the various nodes represent computational tasks and the lines connecting each step are the informational inputs and outputs for each step. Each step can either be automated, such as an analytical task, or semi-automated, where external input and responses are required to complete the steps.

Distance to Target

Comparing indicator-parameter values to a reference or target condition is a critical step in the Framework. It is where sustainability meaning is attached to the data. There are a variety of ways to measure and normalize measurement of parameter conditions to target or reference conditions (see Appendix A for more detail).

In the Framework, normalization is carried out where each indicator evaluated is compared to a pair of reference or standard values (axiological normalization). For each indicator, there is a reference for “poor condition” (score = 0) and “good condition” (score = 100). When this is done for each indicator and each time point, the result is a “distance to target” value that is on a 0-100 scale. An important benefit of comparing indicator condition to targets is that scores can be combined across very different indicators (e.g., water temperature and fish tissue mercury concentrations), whereas otherwise this would not be possible. Because all indicator conditions are quantitatively compared to a target, they are all normalized to the same scale — distance to target. Once the normalization takes place, the new values, ranging from 0 to 100, mean the same thing and can therefore be compared, or aggregated. Because environmental and socio-economic processes and conditions rarely respond to influences in a linear fashion, evaluating indicators

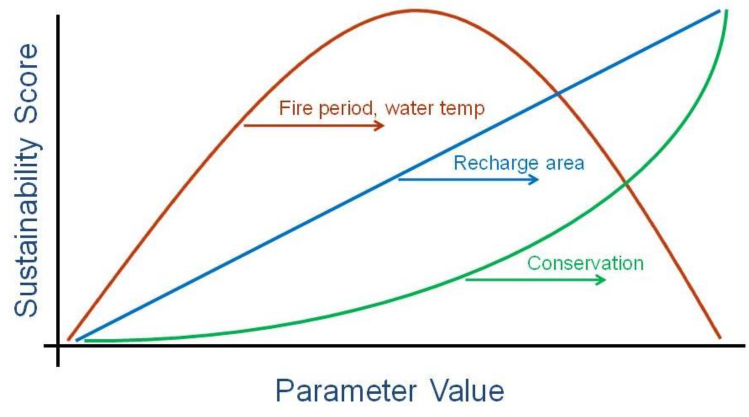


Figure 4. Non-linear relationships between parameters and equivalent sustainability scores.

relative to reference conditions must also take into account these non-linear responses. For example, evaluation of water temperature should follow a non-linear function because, as shown in Figure 4, biological processes may respond non-linearly to changes in temperature. As also shown in Figure 4, other processes or attributes may have a linear relationship, or power relationship to sustainability score.

Trends Analysis

Changes in indicators over time are an important part of sustainability assessment, and while one of the most valuable types of information conveyed with indicators, they are also rarely conducted using appropriate statistical techniques. Analysis of trend in time series data is necessary to determine if conditions in a waterway, community, ecosystem, or watershed are improving or deteriorating. One of the most common techniques for determining trend is linear regression. However, linear regression requires certain data characteristics, such as normal distribution of values, which are not easy to assess in small data sets. Distribution-free trend analysis is ideal due to the unknown nature of the data, so non-parametric methods are better suited for these data. Of the various available non-parametric methods, the Mann-Kendall rank correlation trend test is considered one of the strongest (Berryman et al. 1988). It is appropriate for data that are not normally-distributed, tolerates missing values, and is relatively unaffected by extreme values or skewed data. Related to the Mann-Kendall test, the Seasonal-Kendall test can be used to determine whether or not significant changes have occurred over time, while taking into account variation due to seasonal effects (Hirsch et al., 1982; Hirsch and Slack 1984; Esterby 1996).

In contrast to the non-parametric approach noted above, Nur (Appendix to Collins et al., 2011) proposes the use of fitted regression models to log-transformed values for environmental variables, using bird abundance as an example. Nur incorrectly characterizes non-parametric tests as not being "quantitative" (e.g., the B-slope estimator in Seasonal-Kendall analysis; Hirsch et al., 1982). However, he does make a good case for carefully using quantitative, parametric trends analyses, at least on changes in populations of various biota and possibly other environmental attributes, over time. He also points out that auto-correlation should be measured in trends analyses, in order to estimate the effect on slope magnitude and confidence.

Variance and Confidence

The degree of certainty in the indicator evaluation results depends on two conceptual questions:

1) *whether good indicators were chosen and*
2) *how well the data presented for each indicator accurately reflect the real status or trend in the measurements.*

The first of these questions pertains to the indicators themselves and how well they address the goals/objectives or domains they are meant to represent. Certainty about the indicators depends on four main factors: importance, understanding, rigor, and feasibility.

The second question pertains to statistical confidence in the data presented for each indicator. The available data may contain a variety of sources of uncertainty including: measurement error, uncertain or inappropriate use of the sampling frame, sampling error, and process error. Any of the above sources of uncertainty affects confidence in the estimates of status and reduces the ability to detect trends over time. For some indicators quantification of different sources of uncertainty in the data may be possible, but in many cases there are limited to providing a qualitative description of the likely sources of error and associated magnitude. Reporting confidence, certainty, and/or variance is important to building trust for the indicators framework.

Step 5: Describe Condition and Trend in Report Card

Describe summary condition and trend in condition in an online report card; evaluate performance of system sectors

The Framework report card is the formalized reporting mechanism for indicator condition, trend in condition, and confidence in the findings. Indicator report cards should be understandable to the audience who is intended to benefit from indicator evaluation; it should be accurate and transparent; and it should aggregate information to a degree that does not mask especially poor or good conditions in the study area.

A sample summary report card that measures progress toward meeting objectives and shows summary trend and confidence information is presented in Figure 5.

Goals	Measurable Objective	Condition	Trend	Confidence
Water quality and supply for natural and human communities	Water quality for aquatic health	50	↔	Medium-high
	Maintain natural stream flows	55	n/a	Medium
Protect and restore native animals and plants	Native birds	100	↔	Medium
	Native invertebrates	46	↔	High
	Native fish	49	↔	High
	Agricultural/urban development	90	n/a	Medium
Protect and enhance habitats, ecosystems, and watersheds	Protect aquatic connections	77	n/a	Medium-high
	Protect landscape connections	33	n/a	High
	Maintain natural production and nutrient cycles	82	↓	Medium
Maintain and restore natural disturbance	Restore natural fire regimes	9	↔	Medium
	Encourage natural flooding, while protecting people	50	n/a	Low
Improve social and economic conditions & benefits from healthy watersheds	Enhance wildlife-friendly agriculture	83	↑	Medium-high
	Improve community economic status	51	↓	High

Figure 5. Sample report card, Feather River Basin (Source: Shilling et al., 2010)

Effective online reporting of indicators assessment via the Framework requires a conceptual framework for how information will flow and be provided in ways that people can relate to the information and use it to inform decisions. One approach is to represent and report findings for indicators both geographically and by indicator. These are two common ways that people search for information, but there may be other mechanisms.

Effective online reporting of the Framework requires a model for the corresponding web framework (Figure 6; described in more detail in Appendix F). In this model, information is sorted in two main ways in reporting – geographic and by indicator. Another possibility is to develop a real-time, online indicator system that takes parameter values available online and uses the steps described in the Framework to convert data streams into measures of sustainability in an automated way. A third possibility is to provide ways for data entry to be more automated and mechanisms for a user/decision-maker to adjust data sources, data analyses, and normalization approaches to create ad hoc "what-if" scenarios. This more dynamic system could be a fully built decision-support tool for assessing sustainability and to improve decisions intended to support sustainability.

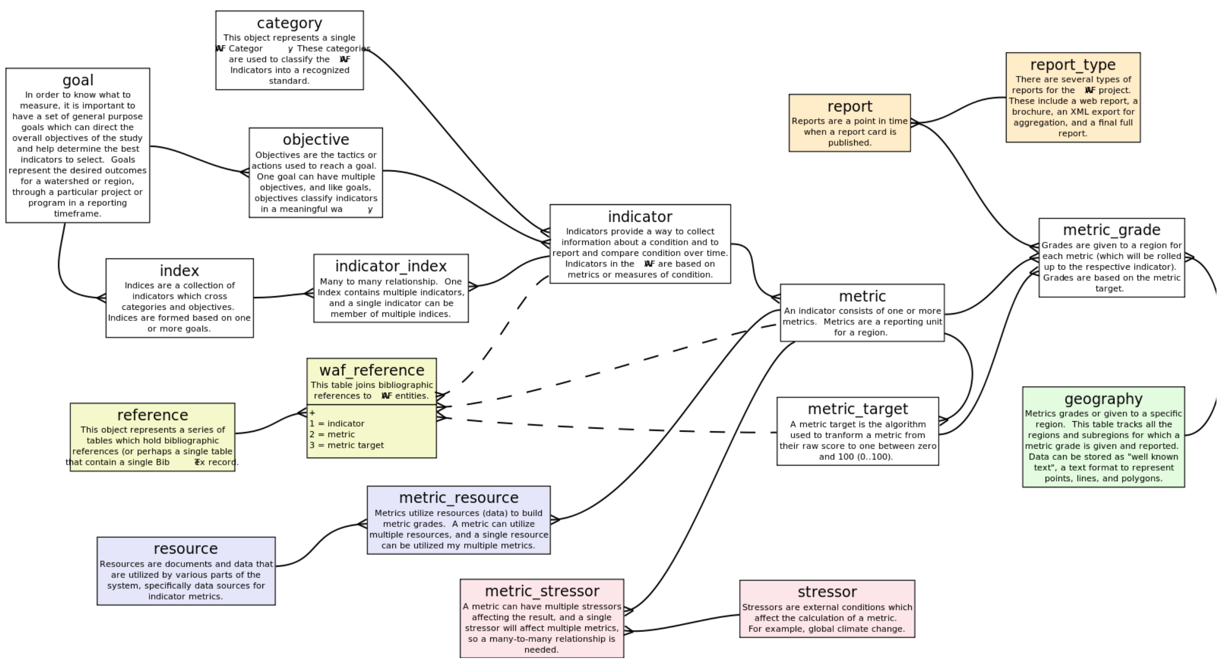


Figure 6. Data model for web-version of a sustainability report card

Step 6: Build Knowledge

Evaluate causes of condition departure from target condition and individual and programmatic actions that could maintain good conditions and repair poor conditions

Evaluating indicators provide a periodic or continuous stream of several types of information. This information contributes to building knowledge about how systems work, how they are changing, how they might change, and what we can do to ensure or build sustainability in these systems. One type of contribution is improved knowledge about the functioning of usually-complex systems by the public and decision-makers. This can help management agencies and elected bodies to make tough decisions if others understand what led to that decision. To facilitate this decision making process, the Framework should include indicators that both measure progress toward meeting social goals and objectives and represent many aspects of complex systems.

Step 7: Describe Change in Policy and Behavioral Response

Describe contribution of evaluation to change in scientific knowledge, policy effectiveness, and public/decision-maker education

Achieving sustainability requires measuring social, economic, and environmental condition and developing actions and policies to respond to degraded conditions and to promote improving conditions. Developing appropriate responses requires accurate condition assessments and linkages between influences and condition change. Developing responsive behaviors and policies is the hard work of the Framework. It will often require negotiation among competing interests, who may question the information provided by the Framework. To help with this process, the report card should convey the relative confidence, or certainty, in the condition assessment. Condition and trends assessment combined with confidence and transparency can provide the basis for sustainable policy and behavioral responses.

2.2. Intersection of Indicators with Natural and Management Systems

Indicators and IRWM Regions and Planning

The California Water Sustainability Indicators Framework is envisioned as a transparent and documented framework for evaluating California's water sustainability, embodying a clear and consistent stakeholder driven vision, a step by step methodology, a suite of indicator reporting methods, a set of consistent terminologies, and important references. It is conceived as a tool for monitoring progress towards the state's water resources sustainability through meeting the objectives of the California Water Plan through a set of relevant, quantifiable indicators. One of the significant anticipated utility of the Framework is that it will provide a toolbox, useful templates, and a set of illustrative examples for IRWM regions to conduct water resources sustainability indicators analysis for local and regional water management. By utilizing this Framework, local and regional water agencies comprising the IRWM regions may be able to improve their water resources sustainability through an evaluation of condition and trends of relevant indicators reflective of their particular needs. This process may also help identify issues and data gaps to inform future data monitoring needs on a local and regional scale to enable better quantification of water resources sustainability indicators in the future. Similar to that for the state as a whole, the indicator analysis on a local and regional scale by the IRWM regions is also expected to highlight policy needs for ensuring the local and regional water resources sustainability. In Phase 2 of the project, we worked with the Santa Ana Watershed Project Authority (SAWPA) to determine how the Framework can be used and refined to suit the needs of regional and local planners and organizations. The associated region-scale results for SAWPA are presented in a companion document titled, "California Water Sustainability Indicators Framework: Assessment at State and Region Scales" as well as on SAWPA's web-site at http://www.sawpa.org/wp-content/uploads/2014/01/Appendix-A-Assessment-of-the-Health-of-Santa-Ana-River-Watershed.pdf. The companion document is also included as an article in the California Water Plan Update 2013, Volume 4 Reference Guide at http://www.waterplan.water.ca.gov/cwpu2013/index.cfm.

Indicators and Ecosystem Services

Ecosystem services were considered in developing the California Water Sustainability Indicators Framework (see Appendix G for a detailed discussion on ecosystem services). Drawing from the scientific literature, a conceptual model for ecosystem services can be built connecting ecosystem processes (e.g., nutrient cycling) and features (riparian forest) to the provision of ecosystem services (e.g., pollination by native pollinators), which in turn provide benefits to humans (e.g., increased agricultural production). Each of these steps can have associated indicators (Figure 7), which not only help describe and quantify the ecosystem services, but can serve to link this concept to the Framework.

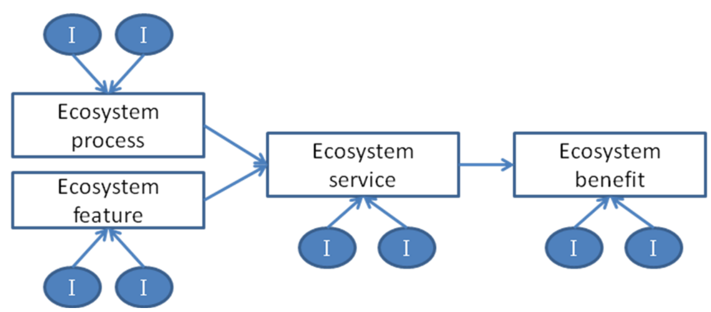


Figure 7. Indicators ("I" in circles) in the ecosystem services model

A companion effort was completed by a separate Water Plan work team to quantify ecosystem services and the associated benefits. The Framework effort collaborated with the Water Plan ecosystem services effort to ensure consistency between the two. This collaboration is anticipated to continue in Water Plan Update 2018.

Indicators and Ecological and Water Footprints

An ecological footprint is a measure of the impact humans have on the earth. In the simplest terms, it is a measure of resource consumption and waste production compared with the planet's natural ability to generate new resources and absorb waste. Calculations are based on land area required to produce and assimilate these resources and wastes within six land use types:

cropland, grazing land, fishing ground, forest land, built-up land, and the uptake land to accommodate the carbon footprint (a measure of carbon dioxide release and natural absorption) (Global Footprint Network 2010).

The ecological footprint is a useful indicator for determining sustainability because it incorporates many facets of consumption and renewal in a manner that is measurable and useful in management (Wackernagel and Yount 1998).

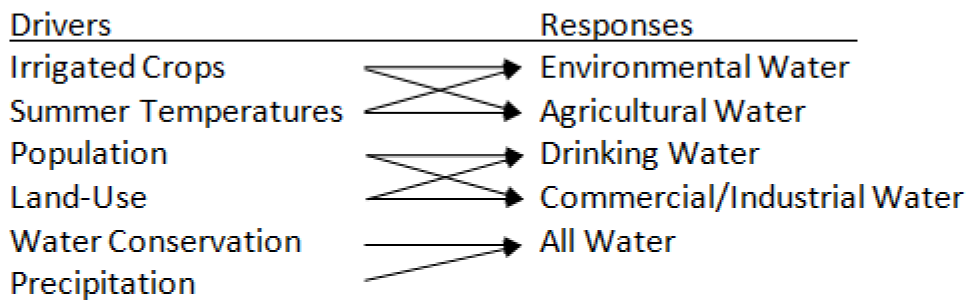
The relevance of the ecological footprint with regards to the California Water Sustainability Indicators Framework is evident in the water footprint, which is derived conceptually and is related to the ecological footprint idea. The water footprint is the sum of the water used directly or indirectly to produce goods and services consumed by humanity. Agricultural production accounts for most of global water use, but drinking, manufacturing, cooking, recreation, washing, cleaning, landscaping, cooling, and processing all contribute to water use (Hoekstra et al. 2011). In addition to these direct water uses, indirect uses such as water impacted by pollutants, chemical or temperature, contribute to the water footprint (see Appendix H for more detailed discussion on ecological and water footprint).

A parallel effort "California Footprint Sustainability Indicators for Decision Support" led by the USEPA has been completed. The two major components of this effort are the development of ecological and water footprints. Global Footprint Network led and completed the ecological footprint analysis. Links to results from this effort are provided at http://indicators.ucdavis.edu.

Indicators and Water Plan Scenarios

An important component of the Water Plan is development of potential scenarios for populations, land-use patterns, irrigated crop area, water conservation, precipitation, and temperatures. In combination, these parameters can be used to model water management under possible future conditions. In an attempt to describe boundary states for possible future conditions, the Water Plan Update 2009 solved for a combination of conditions for each parameter in the following three scenarios: Current Trend, Slow/Strategic Growth, and Expansive Growth.

The primary parameters in scenario modeling can be treated as drivers in the water cycle that have measurable responses: environmental, agricultural, drinking, commercial/industrial, and all water. Indicators for both the drivers and responses can be and are included in the Framework. This allows potential future conditions and management responses to be modeled and assessed in the context of the Water Sustainability Indicators Framework.



2.3. Where We Were and Where We Are Going

Where We Were:

The Water Plan Update 2009 included a brief discussion of using indicators to understand water-related conditions in California and how management could be improved to make water management more sustainable. In early 2010, California Water Plan's work team initiated the development of the California Water Sustainability Indicators Framework. Through a series of internal discussions over a period of several months in 2010, the work team developed a project charter for the Framework. Further discussions were held with the Sustainable Water Resources Roundtable, the Bay Institute, the Delta Stewardship Council, and the Strategic Growth Council during 2010 and 2011. Based on these discussions, the project charter was revised accordingly.

As part of Water Plan's outreach process, the project vision, objective, and deliverables were introduced to the State Agency Steering Committee, the Public Advisory Committee, and the Tribal Advisory Committee. Based on their feedback, the project charter was further revised.

In early 2011, DWR engaged UC Davis to provide technical support to the project to assist in the development of the Framework, based upon earlier indicator system development by UC Davis in three regions of California (Shilling et al., 2010 & 2011; Antos et al., 2011). During the same time, USEPA Region 9 initiated and finalized discussions with DWR to collaborate in the project through financial and advisory support.

Phase II: Pilot Testing of the Framework

The Framework has been in development until the Water Plan Update 2013 was finalized. It underwent periodic review by the Water Plan Sustainability Indicators Workgroup with interagency participation, the Public and Tribal Advisory Committees, and other agencies and individuals.

Meetings and Workshops

The Framework was presented to the Sustainable Water Resources Roundtable (SWRR) in winter 2011. This was an important presentation and review because the Roundtable represents water agency officials and scientists from throughout the country. The Framework was discussed at the Water Plan plenary meetings in 2012 and 2013 to incorporate the perspectives of various stakeholders. Periodic vetting and discussion of the Framework complemented the Phase II pilot implementation of the Framework described below.

California Water Sustainability Indicators Framework: Assessment at State and Region Scales

The framework was pilot tested at the scale of California and in one region of the state in order to test its effectiveness.

1) Using seven criteria, UC Davis, DWR, and USEPA staff evaluated 14 candidate regions for their potential role as pilot regions. The criteria were:
    a. the region represents a cross-section of the wide range of activities and natural conditions of California;
    b. working with the region will assist with regional management needs and meet state-level/Water Plan management needs;
    c. medium-quality data is available for a cross-section of indicators;
    d. the region has the capacity and desire to engage with the project team;
    e. the region has a coastal connection;
    f. the area represents a cross-section of the wide range of activities and natural conditions of the region; and
    g. the region is a good candidate for regional water footprint analysis.

Using these criteria, the following five regions were selected for further evaluation and discussion with regional planners: Santa Ana River watershed, Silicon Valley, Sonoma County, Northern Sacramento Valley Integrated Regional Water Management project, and the San Joaquin Valley Partnership.

The Santa Ana Watershed Project Authority (SAWPA) enthusiastically partnered with us and regional partner, the Council for Watershed Health to pilot the approach and evaluation of individual indicators for water sustainability in SAWPA region.

2) Interaction with regional stakeholders regarding regional objectives and data sources. The Framework approach is based upon stakeholder goals and objectives, so an early step was for the Framework team to elicit goals and objectives from stakeholder agencies and organizations. This step depended on a close partnership and clear communication between our team and regional partners.
3) Indicator selection, indicator data collection and analysis. After discussion with regional and state stakeholders, indicators were selected (primarily from the recommended indicators in the Framework). Data were gathered from local, regional, and state resources corresponding to each of the indicators. The data were managed so as to allow others to access the data as part of provenance for the indicator evaluation and reporting.

Targets were selected for each indicator, based on the scientific and technical literature and expert knowledge. Each indicator was evaluated using the distance to target method. California's water footprint and its trend over time were evaluated for the state in collaboration with the Pacific Institute, who has already begun such a calculation.

4) Publication of a water sustainability report for the region. After discussion with state and regional stakeholders, a reporting mechanism was selected (i.e., an online report card) that effectively conveyed the findings of the pilot implementation of the Framework in an understandable format and level of complexity. This implementation of the Framework included use of the "water footprint" as an important index of water use impact. Detailed results from the state and region scale pilots as well as issues and gaps associated with using the Framework at the state and region scales are provided in a companion document titled, "California Water Sustainability Indicators Framework: Assessment at State and Region Scales" as well as at http://indicators.ucdavis.edu. The companion document is also included as an article in the California Water Plan Update 2013, Volume 4 Reference Guide at http://www.waterplan.water.ca.gov/cwpu2013/index.cfm.

   A proof-of-concept Decision Support Tool for visualizing the data from the pilot tests of the Framework as well as USEPA's "California Footprint Sustainability Indicators for Decision Support" is available at http://indicators.ucdavis.edu.

Finalizing the Framework

The Framework was initially developed at the end of 2011. By the end of pilot testing in Phase II, the Framework was refined based on feedback received and lessons learned. This report documents the final Framework developed and updated as part of the California Water Plan Update 2013.

Coordination with Related Efforts

- **USEPA:** DWR and UC Davis have closely collaborated with USEPA's California Footprint Sustainability Indicators for Decision Support project. The two major components of the project are the development of ecological and water footprints. USEPA engaged Global Footprint Network to conduct the ecological footprint analysis at the State of California level to compare the population's use of natural resources with the ecosystem's ability to provide those resources. In partnership with USEPA, DWR and UC Davis worked with the Pacific Institute to estimate California's water footprint and its trend over time.
- **Strategic Growth Council (SGC):** The SGC is an inter-agency collaborative organization, established in 2008, that is intended to support sustainable land, air, and water conditions and community well-being. DWR and UC Davis coordinated with SGC in order to improve alignment of the indicator analysis carried out in SGC's regional reports with the Framework. In the first iteration of this coordination, water sustainability

indicators may be adopted by the SGC regional reports as the method to measure this aspect of environmental, economic, and community well-being. In future work, we hope that the methods used in the Framework and the SGC regional reports will become more similar.

- **Regional Agencies:** UC Davis and DWR have coordinated with several local and regional partners and companion efforts to encourage more coordination among similar efforts in California. The Sonoma County Water Agency partnered with the California Water Foundation on developing a similar framework in watersheds and counties of the North San Francisco Bay. DWR has been closely coordinating with the California Water Foundation on this effort. The UC Davis also worked with the Sacramento Regional County Sanitation District on developing a water quality report card for the Lower Sacramento River that was consistent with the water quality components of the Framework.
- **State Agencies:** Following the example set by California Water Sustainability Indicators Framework, California Department of Forestry and Fire Protection (CAL FIRE), with assistance from UC Davis, is exploring applying a similar concept in their upcoming California Forest and Range Assessment Report.

  Following the example set by the Framework, California Biodiversity Council (CBC) formed the CBC Indicators Group with core membership from CAL FIRE, DWR, California Department of Fish and Wildlife (CDFW), and US Forest service (USFS) with the goal to collaboratively develop and assess a common set of environmental sustainability indicators across major planning programs which occur in California through a shared framework to report on indicators.

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Appendix A. Extended Glossary of Terms

This appendix provides a list of terms useful in communicating effectively and ensuring consistency among similar sustainability indicator systems.[1] The terms and definitions are primarily based upon the work of three regional California Watershed Assessment Framework (CWAF) projects conducted between 2008 and 2011.[2] The CWAF was built to meet watershed monitoring needs and performance measures identified in the California Watershed Management Strategic Action Plan. The terms and definitions originated from a combination of reports and background documents from state, federal, and global efforts towards developing social and ecological condition reporting frameworks for monitoring condition and performance.

Sustainability Indicators Framework

The Sustainability Indicators Framework is in an evaluation framework developed for use at the scale of natural or jurisdictional land units. The concept and use of the Framework is partially based upon the CWAF structure and process, which was in turn based upon an approach developed by the USEPA's Science Advisory Board and has been adapted

The Framework provides a scientifically defensible approach for aggregating and assessing a variety of environmental, economic and social information. The Framework can be used to assist in linking the condition of a study area's natural and social conditions into a broad framework consisting of the sum total of the physical, chemical, social and biological components of the study area and how they interact and change over time. The Framework includes approaches and indicators for evaluating of economic and social conditions and is a way of integrating consideration of environment, economics, and equity/social conditions at natural or jurisdictional scales/extents. The Framework acknowledges that humans and their activities are integral parts of ecosystems and that most human endeavors depend upon healthy natural systems.

Systems

Indicators are usually chosen to represent parts of complex systems. A system, as the term is used here, is a set of interacting parts, where both the components and the relationships among them is part of the system. For example, an ecosystem is composed of interacting organisms and natural processes, social and economic systems are composed of interacting people and organizations/institutions. Typically, economic systems as defined by financial or other material exchanges and conditions, while social systems are the remaining conditions (e.g., health). It is usually important when using this term to define the boundary conditions for the particular application of the term.

[1] http://www.water.ca.gov/watersheds/framework.cfm
[2] Developed by Fraser Shilling (UC Davis) based on the index/indicator literature and feedback from Jeff Sharp (Napa County) and Mike Antos (Los Angeles San Gabriel Rivers Watershed Council).

Social and Ecological Themes, Domains or Categories

A category is a class of similar concepts, ideas, or things within in an organized and rule-based system to discriminate among classes where the discrimination is based on apparent differences among the categorized objects. Themes and domains are types of category and are terms of art referring to large parts of natural or social systems (e.g., landscape condition). Categories, themes and domains are one way to organize information in an overall condition index, like the Framework, where the categories and sub-categories are used to classify related indicators (Figure 1).

The 8 essential attributes identified in the CWAF valuation projects is a means to categorize various attributes that describe a watershed and are described below.

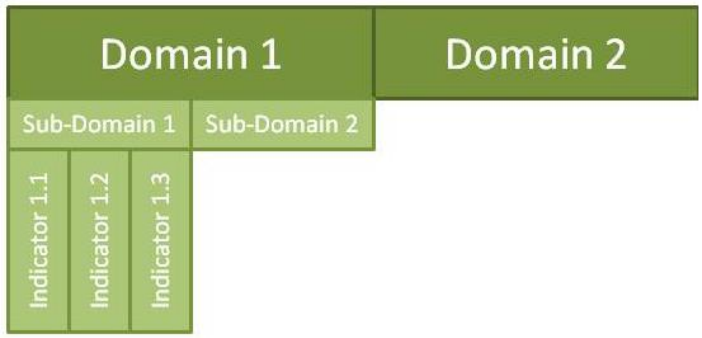

Figure 1. Indicators nested within sub-domains, in turn nested within domains

Landscape Condition

The extent, composition, and pattern or structure of (non-human) habitats in a landscape.

Biotic Condition

The condition or viability of communities, populations, and individual biota (i.e., at the scale of individual habitat types).

Ecological Processes

Metabolic function of ecosystems - energy flow, element cycling, and the production, consumption, and decomposition of organic matter at the ecosystem or landscape level.

Social Condition

The examination of the organization and development of human social life within the watershed, including measurements of community and social patterns, and behavior of individuals and groups.

Economic Condition

Measures of the production, distribution, and consumption of goods and services within a watershed, including the valuation and of non-market resources that provide individual and community utility.

Chemical and Physical Characteristics

Physical parameters and concentrations of chemical substances present in the environment/watershed (water, air, soil, sediment).

Hydrology/Geomorphology

Characteristics that reflect the dynamic interplay of surface and groundwater flows and the land forms within the watershed.

Natural Disturbance

The historical and/or contemporary function of discrete and usually recurrent disturbances, which may be physical, chemical, or biological in nature, that shape watershed ecosystems.

Goals and Objectives

*"**Goals and Objectives.** Ideally, environmental management programs begin with a process to develop goals and objectives that articulate the desired ecosystem conditions that will result from the program(s)." (USEPA SAB Report)*

Goals describe desired outcomes for a watershed or other natural or social system, through a particular project or program in a stated timeframe. In the case of the Framework, goals are described in the California Water Plan, relating to the desired outcomes for the study area in some stated timeframe.

Objectives are the tactics to the goals' strategies. They describe actions that can be taken to implement or reach goals and are often nested within goals (Figure 2). Objectives for systems can be defined as actions that help reach desired outcomes for particular aspects of the system's condition.

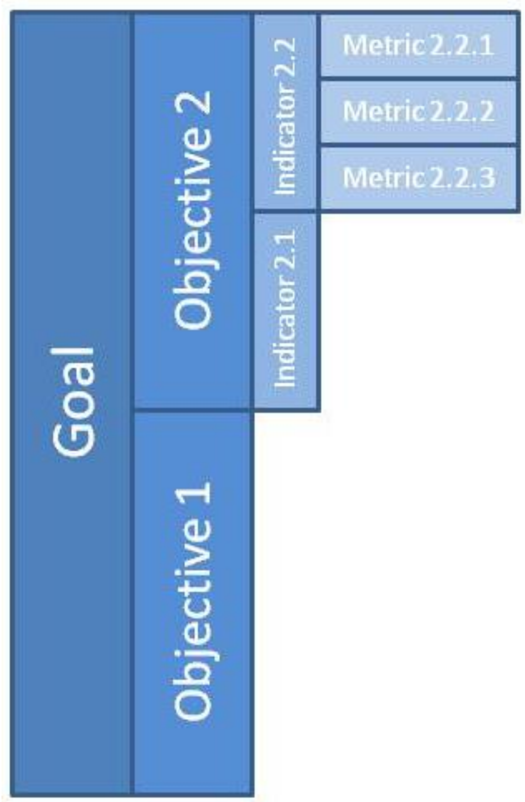

Figure 2. Nested metrics, indicators, and objectives within goals

Index

Sometimes organizations want to develop a comprehensive understanding of environmental or social health and express that as a single score, which is a composite of several or many indicators. This composite is usually called an index. In terms of the Framework, you could imagine scores for indicators within a domain called "water quality" being composited into an overall attribute score for water quality. In this case, the domain is functioning as an index.

Indicators

*"**Ecological Indicators** (also called ecological endpoints) are measurable characteristics related to the structure, composition, or functioning of ecological systems. Multiple indicators may be associated with each subcategory in the EEA [essential ecological attribute] hierarchy." (USEPA SAB Report)*

Indicators (the backbone of the Framework process) provide a way to collect information about a condition and to report and compare condition over time. As noted previously, indicators in the Framework are organized within domains (Figure 1) and goals/objectives (Figure 2), and are based on metrics or measures of condition. Sometimes indicators and metrics are the same thing. For example, "surface water temperature" is a metric; something directly measured in nature, and also considered an indicator. In contrast, "fish population" is an indicator and may be measured using any of several possible metrics (e.g., number of returning spawning adults).

Metrics/measures

*"**Measures.** The measures are the specific monitoring variables that are measured in the field and aggregated into one or more ecological indicators." (USEPA SAB Report)*

Metrics/Measures are the building blocks of indicators and thus the foundation of a condition assessment system. Examples of metrics and measures include dissolved oxygen concentration, proportion of successful nests (i.e., produce young) per season for a particular riparian bird species, and fire return interval for a particular plant community within a study area. Each of these measures might fit into an indicator composed of one or more metrics (e.g., "fire dynamics") that in turn is categorized into a system domain (e.g., natural disturbance) or goal.

Variance and Confidence

The degree of certainty in the Report Card results depends on two conceptual questions: whether good indicators were chosen and how well the data presented for each indicator accurately reflect the real status or trend in the metric(s). The first of these questions pertains to the indicators themselves and how well they address the objectives or attributes they are meant to represent. Certainty about the indicators depends on four main factors: Importance, understanding, rigor, and feasibility.

- **Importance** — the degree to which a linkage (functional relationship) controls the outcome relative to other drivers and linkages affecting that same outcome,
- **Understanding** — the degree to which the performance indicator can be predicted from the defined linkage (functional relationship) and its driver(s),

- **Rigor** — the degree to which the scientific evidence supporting our understanding of a cause-effect relationship (linkage) is contested or confounded by other information, and
- **Feasibility** — the degree to which input data necessary to calculate the proposed performance measure can be delivered in a timely fashion (without external bottlenecks) and the amount of effort (relative to other possible indicators) needed to implement the cause-effect linkage in a computer model.

The second question pertains to statistical confidence in the data presented for each indicator. The available data may contain a variety of sources of uncertainty including: measurement error, uncertain or inappropriate use of the sampling frame, sampling error, and process error.

- **Measurement error** — Random or systematic errors introduced during the measurement process, sample handling, recording, sample preparation, sample analysis, data reduction, transmission and storage (USEPA 2006; Thompson 2002)
- **Uncertain/inappropriate interpretation of sampling frame** — Errors in inference resulting from opportunistically mining the available data without knowledge of the sampling frame1. For example, macro-invertebrate data may have been collected by several different studies with different objectives and target populations (e.g. they could have focused on different stream orders). Without this knowledge, we must make assumptions about the probability of selecting each site and the appropriate weighting of the observation.
- **Sampling error** — The error resulting from only examining a portion of the total population (Cochran 1977; Lohr 1999; Thompson 2002), if a census of the population is taken (e.g., school lunch enrolment) then there is no sampling error.
- **Process error** — Actual variability between spatial or temporal units in the population. This source of variability exists even if a census is taken with no measurement error. This is often referred to as natural variability.

Any of the above sources of uncertainty affects confidence in the estimates of status and reduces the ability to detect trends over time. For some indicators quantification of different sources of uncertainty in the data may be possible, but in many cases there are limitations to providing a qualitative description of the likely sources of error and associated magnitude. Reporting confidence, certainty, and/or variance is important to building trust for the indicators framework.

Distance to Target

Comparing indicator-parameter values to a reference or target condition is a critical step in the Framework. It is where sustainability meaning is attached to the data. There are a variety of ways to measure and normalize measurement of parameter conditions to target or reference conditions.

The table below summarizes the main methods, their advantages and disadvantages.

<table>
<tr><th colspan="2">Method</th></tr>
<tr><th>Advantages</th><th>Disadvantages</th></tr>
<tr><td colspan="2">Empirical normalization
Min max method gives the 0 value (Min) to the most unfavorable observed value and 1 or 10 (Max) to the best recorded value. All intermediary values are calculated based on the formula: Y = X – Min/(Max – Min).</td></tr>
<tr><td>Simple and efficient to compare alternatives with an initial state</td><td>Variability of Min and Max values that depend on observed values, new observation outside the previous limits will lead to new normalization. Extreme values/or outliers could distort the transformed indicator</td></tr>
<tr><td colspan="2">Axiological normalization
Close to the empirical approach with min and max limits. The limits are not statistically identified, being chosen based on the undesirable situation, which receives the “0” value, and on the ideal situation, which can or cannot correspond to a strategic objective and which receives the value “1”.
Alternatives to min and max here are :
• distance to a reference method that takes the ratios of the indicator to a value of mean reference for this indicator: $Y=X/X_{expected}$
• Indicators above or below the mean : this transformation considers the indicators which are above and below an arbitrarily defined threshold, p, around the mean $X_{expected}$:
$$Y = \begin{cases} 1 \ if \ \dfrac{X}{X_{expected}} > (1+p) \\ 0 \ if \ (1-p) < \dfrac{X}{X_{expected}} < (1+p) \\ -1 \ if \ \dfrac{X}{X_{expected}} < (1-p) \end{cases}$$</td></tr>
<tr><td>Simple and efficient to compare alternatives.
Reduced impact of extreme values</td><td>Might be less realistic than the empirical approach because limits depend on objectives, not on observations</td></tr>
<tr><td colspan="2">Mathematical normalization
Transformation of data by means of a mathematic function in order for the values to range between an upper and a lower limit</td></tr>
<tr><td></td><td>Lack of transparency for the user and possible change of initial distribution of values</td></tr>
<tr><td colspan="2">Statistical normalization
All values are expressed in standard deviation, so that the variables average is equal to zero</td></tr>
<tr><td>Does not depend on min and max values determined by strategic objectives or statistics</td><td>Does not depend on min and max values determined by strategic objectives or statistics</td></tr>
</table>

This measurement of distance to a target or reference condition is sometimes called the "ideal point" method (Malczewski, 1999). The ideal point method was first introduced in the late 1950s and expanded by Milan Zeleny in the 1970s (Pomerol and Barba-Romero 2000). Zeleny (1982) described the measurement of closeness with: $d_i = f_i^* - f_i(x_{ji})$ where d_i is the distance of attribute state x_{ji} to the ideal value f_i^*, i indicates the attribute and j indicates the objective.

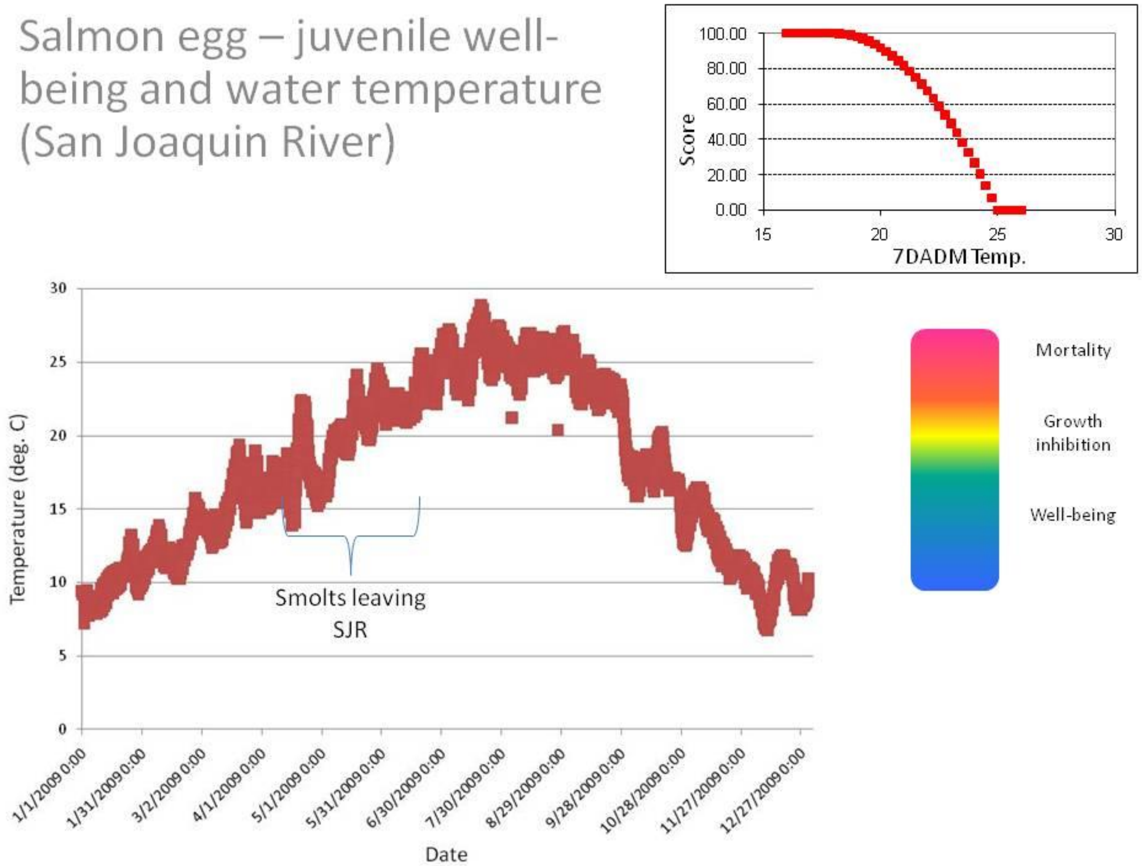

Figure 3. Comparison of salmonid young well-being to San Joaquin River water temperature. Inset graph: relationship between temperature and score for water temperature, based upon temperature sensitivity of salmonid young.

Appendix B Indicator Selection Criteria

Availability of high-quality data

One of the main obstacles many face when selecting indicators is the lack of available data. Frequently the data for an indicator that may be important are not available. Alternatively, the data might only be available for random points in time or for limited geographical areas. The data might have been collected for one purpose in a particular way that served the original purpose, but for your purposes, it may be inadequate. If new data are needed, the feasibility of collecting them might be limited by the amount of effort required to accurately make the measurement (e.g., actual salmon escapement). Alternate indicators may be considered that have significantly lower cost (e.g., remote-sensing based habitat assessment). For certain indicators, it may be very cost-effective to collect the required metrics (e.g., habitat assessment for a species of concern), but the indicator may not represent the process of concern compared to more expensive indicators (e.g., actual population trends in the species of concern). Data collection and analysis costs (further described as a separate criterion below) have to be evaluated in relation to the potential cost and societal implications of a proposed action or inaction, i.e., the greater the expected tradeoffs between societal goals, the greater the need for certainty in the environmental outcome. When choosing indicators, it is essential to carefully consider the current availability of data for the indicator, as well as how much data will be available in the future from our own collection and from the efforts of others. The availability of metadata is one criterion for selection of particular data for corresponding indicators. Finally, indicators will be useful and useable in the long-run if there is a process for updating the corresponding database, metadata, and data collection & QA/QC procedures.

Long-term data affordability

One factor to consider in evaluating indicators is the costs associated with collecting and analyzing data. One consideration in evaluation the costs and benefits is the usefulness of the information for evaluation of management and ecosystem condition. Indicators that are cost-effective, while accurately representing ecosystem characteristics are preferable. The primary guide is that the amount of data required to adequately report on condition and change in condition can be and are being collected with the resources available. The data should also be collected in a standardized way for which there are QA/QC procedures described. For critical indicators (those reflecting important system conditions for which there is no viable alternative), more resources may need to be made available if they are currently inadequate.

System representation

Another factor to consider in indicator selection is how well the indicator reflects the issue for which it was selected. Frequently, certain indicators are widely recognized to be a useful measure for an issue. Selecting these indicators is usually a ‘safe bet’. For example, percent riparian canopy cover is considered a good indicator of riparian conditions because it has been extensively studied and shown to have a good relationship with stream temperature and the detection of changes can be made easily. Selecting indicators that have been carefully evaluated for their scientific validity means they usually have wider acceptance than those that haven't been studied very much, and they are more likely to allow you to make confident inferences about system condition. Indicators that are representative of large aspects of system condition and trends are preferable for those that have narrower utility, all else being equal. Sometimes the condition is itself an important ecosystem driver. For example, surface water temperature is an important ecological variable for understanding the condition of aquatic ecosystems. It is also the target of management actions to benefit these ecosystems, which is another criterion described below. Indicators that can provide important information at both broad and fine spatial scales are likely to be more useful as they can help inform both strategic and site-specific decisions.

Sensitivity to change over time

The ability to report on trends over time is a key function of an indicator. The availability of a data set collected over a period of many years is ideal. Indicators that respond relatively quickly to management intervention and can effectively be used to measure change over time may be preferable to those that require data over long periods of time to observe changes due to management actions. This is especially useful in reference to short-term grants and contracts, or short-term program evaluation, which require performance measures to demonstrate the success or failure of the project. If possible, select indicators whose range of natural variation can be quantified and that permit change detection over short periods of time (2-3 years). At the same time, recognize that many of the processes that we try to improve with restoration programs take decades or longer to change or recover (e.g., salmon population recovery). Indicators for these projects and programs should be stable over these longer timeframes (i.e., decades).

Independence of indicators from one another

Independence refers to how related indicators are to each other. Road density and %impervious surface are related indicators because roads are often impervious. Indicators that are relatively independent are preferable (e.g., rate of ground water use for irrigation and migration barriers), while recognizing that some critical indicators are related and somewhat dependent on each other (e.g., surface water temperature, flow, stream shading, hydraulic connectivity to groundwater, salmon rearing habitat suitability). The concern about independence is important for designing efficient indicator systems, but is secondary to choosing easily-measured and representative indicators. You may choose related indicators, but you would be constrained in your attempts to use them together to explain condition of a system. For example, if (a) surface water temperature, (b) flow, (c) stream shading, (d) amount of groundwater withdrawal, and (e) salmon rearing habitat were indicators of success for a restoration program, then you could not report changes in these indicators without acknowledging that (a) depends on (b), (c), and (d); (e) depends on (a), (b), (c), and possible indirectly on (d) through (b); and (c) may depend on (b) and (d). If restoration of riparian shade (c) was a goal in order to benefit salmon rearing (e), then the inter-dependence of some of the other parameters would need to be acknowledged and potentially controlled-for in order to measure the true effect of increased riparian shade on salmon rearing.

Supports management decisions and actions

Measuring conditions in the environment and in communities can inform policy development and social/fiscal investments. Indicators should be informative in evaluating environmental/social/economic conditions, as well as the influences on these conditions. Another useful characteristics of indicators is that they can be used to evaluate the effects or effectiveness of management actions — be it a state or federal agency or the goals and

objectives of a watershed council. Whatever the business of the organization is, indicators should provide information that can be used to assess the effectiveness of the work and efforts of the group. In the past, activities were seen as a measure of the effectiveness of an organization. The number of grants awarded, the number of pamphlets distributed, or similar “bean counting” has been used extensively to evaluate an organization’s productivity. Performance measures, on the other hand, look at the environmental and social outcomes of these activities to determine an organization’s effectiveness. This is the reason it is so important to select indicators that are closely linked to management actions and decisions and that can be reported and understood in public arenas. The point of most indicators is to inform a wide audience about conditions in the environment and communities. Indicators should be science-based and easily understood by various kinds of decision-makers (e.g., scientists, public, elected officials). They should be equally presentable in summary form in newspapers and on web sites. Finally, indicators should be based upon reportable technical & scientific information and links easily made between summary presentations and the source data and knowledge.

Appendix C Indicator Systems from Around the Globe

Learning from Other Efforts in California and the US

The California Water Sustainability Indicators Framework was not developed in isolation. We benefitted from the lessons learned from other similar efforts described below.

Since 2002, the Sustainable Water Resources Roundtable has brought together State, federal, corporate, nonprofit, and academic sectors to advance understanding of the nation's water resources and to help develop tools for understanding and ensuring their sustainability (acwi.gov/swrr/index.html). SWRR has developed a five part framework with a set of 14 key sustainability indicators that can be useful for other entities developing their own indicators.

The Sacramento River Watershed Program beginning in 1996 developed the Sacramento River Watershed Management Plan that included a Roadmap and Watershed Health Indicators Program. The Roadmap provides an overview of the basin's six subregions and a picture of watershed health within the Sacramento River Basin. The Watershed Health Indicators Program uses the Watershed Assessment Framework to better understand some of the relationships between social, economic, and environmental conditions, and watershed management actions. The Watershed Health Indicators Program Report Card effort was launched in 2008, focusing on the Feather River Watershed for tracking watershed conditions and trends.

The Bay Institute Ecological Score Card was first produced in 2003 and then updated in 2005; another update is anticipated in 2013. In 2005 update, more than three dozen science-based indicators have been used to grade the condition of the Bay region. These indicators were combined into eight indexes. The score card system compares current conditions in the Bay and its watershed to: historical conditions, environmental and public health standards, and restoration targets.

State of the Great Lakes 2009, an undertaking by the U.S. EPA and Environment Canada, used Environmental Indicators for assessing status and trends of the Great Lakes Ecosystem (Lake Superior, Lake Michigan, Lake Huron, Lake Erie, and Lake Ontario). The status of ecosystem components was assessed in relation to desired conditions or ecosystem objectives. The effort assessed 62 ecosystem indicators categorized into 8 different groups.

2010 Environmental Performance Index (EPI) was prepared by the Center for International Earth Science Information Network (CIESIN) at Columbia University. The effort ranks 163 countries on 25 performance indicators, tracked across 10 policy categories covering both environmental public health and ecosystem vitality.

Framework name	Project URL	Complete report URL	Date	Institutional lead	Constituents
An Indicator Framework for Linking Historic Preservation and Community Economic Development		http://www.springerlink.com/content/j3t4186157728877/fulltext.pdf	Mar 29 2011	Arizona State University School of Community Resources & Development	
Sustainable Industries Performance Indicator Framework	http://www.ecoindustrial.ca/usgbc_toolkit/	http://www.ecoindustrial.ca/usgbc_toolkit/SustainableIndustryIndicatorsFinalReport23Mar05_protected.pdf	Mar 23, 2005	Industry Canada's Sustainable Technologies and Service Industries	
Framework for Measuring Sustainable Development in Catchment Systems	http://planet.uwc.ac.za	http://planet.uwc.ac.za/nisl/Gwen%27s%20Files/GeoCourse/Integrated%20Environmental%20Management/IEM/Peer%20Reviewed/Walmsley2002.pdf	2002	Mzuir Consultants, South Africa	
Transport Monitoring Indicator Framework	http://www.transport.govt.nz/ourwork/tmif/	http://www.transport.govt.nz/ourwork/TMIF/Documents/TMIFV2%20FINAL.pdf	2009	Ministry of Transport, New Zealand	
Food Security Indicators and Framework for Use in the Monitoring and Evaluation of Food Aid Programs	www.fantaproject.org	http://www.fantaproject.org/downloads/pdfs/fsindctr.PDF	Jan 1999	US Aid	
Framework to evaluate ecological and social outcomes of collaborative management: lessons from implementation with a northern Arizona collaborative group.		http://www.springerlink.com/content/2u4lk31q6558uu28/fulltext.pdf		School of Sustainability, Arizona State University	

JSEM: A Framework for Identifying and Evaluating Indicators		http://www.springerlink.com/content/p36j1x36832834pl/fulltext.pdf	Dec 1998	Dynamic Corp Environmental Servces, US EPA, Corvallis OR	
A quantitative indicator framework for stand level evaluation and monitoring of environmentally sustainable forest management		http://www.sciencedirect.com/science?_ob=MImg&_imagekey=B6W87-50SJMGB-1-6&_cdi=6647&_user=4421&_pii=S1470160X1000124X&_origin=gateway&_coverDate=03%2F31%2F2011&_sk=999889997&view=c&wchp=dGLbVtz-zSkWA&md5=7bc9184b665e83a1c156a9a97593a610&ie=/sdarticle.pdf	13 Nov 2009	Ghent University (lead author)	
Biodiversity Indicators Partnership	http://www.bipindicators.net/	http://www.bipindicators.net/LinkClick.aspx?fileticket=NYhSvmOUgps%3d&tabid=155	2010	BIP	
Puget Sound Partnership	http://www.psp.wa.gov/	http://www.psp.wa.gov/downloads/SP2009/IndicatorSummaryReport(Final)120108.doc http://www.psp.wa.gov/downloads/SP2009/IndicatorEvaluationSpreadsheet091308.xls	2008	PSP	
Sustainable Water Resources Roundtable	http://acwi.gov/index.html	http://acwi.gov/acwi2008/slide.lib/SWRR-Indicators-Feb05Draft-Part1and2combined_new.pdf	2008	Advisory Committee on Water Information	
Coastal Institute	http://www.ci.uri.edu/	http://www.ci.uri.edu/Projects/PNB/Chafee-HUD/Indicators_Final.pdf	2003	CI – Narragansett Bay Region	

New Hampshire Forest Resources Plan Revision	http://www.na.fs.fed.us/	http://www.na.fs.fed.us/sustainability/pubs/criteria/lessons_learned.pdf	August 2006	USDA – Forest Service	
An adaptive indicator framework for monitoring regional sustainable development: a case study of the INSURE project in Limburg, The Netherlands		http://sspp.proquest.com/archives/vol6iss1/0901-004.vanzeijl.pdf	June 2, 2010	Maastricht University, The Netherlands	
European Environment Agency	http://www.eea.europa.eu/	http://www.google.com/url?sa=t&source=web&cd=117&ved=0CD8QFjAGOG4&url=http%3A%2F%2Fwww.eea.europa.eu%2Fen%2Fpublications%2Ftopic_report_2003_1%2FTopic_1_2003_web.pdf&rct=j&q=indicator%20framework%20water&ei=-kunTaihBYK2sAOs3Kn6DA&usg=AFQjCNFVjxI-s4ADH841VPGij4E5aXoKAA&cad=rja	2003	The EU	
An Indicator System for Surface Water Quality in River Basins		http://repositorium.sdum.uminho.pt/bitstream/1822/4638/1/OLIVEIRA_CI1_2005.pdf	2005	Universidade do Minho, Portugal	Good to read to get sense of how to develop indicators
UN Indicators of sustainable development: framework and methodologies 2001, 2007		2007 version (last one) http://www.uneca.org/eca_programmes/sdd/events/Rio20/WorkshopSDIndicator/SustainableDevelopmentIndicators.pdf 2001 version	2007 April 2001	UN	1. Categories, indicators, methodology, evaluation per country, recommendations. 2. Application at national level 3. Discussion of different type of frameworks

		http://www.un.org/esa/sustdev/csd/csd9_indi_bp3.pdf			4. Topics: health, poverty, governance, education, demographics, natural hazards, land, freshwater, atmosphere, ocean and coasts, biodiversity, economic development, global partnership, consumption and production patterns 5. Currently applying the new version in Africa
	UN Sustainable indicators for Africa	http://www.uneca.org/eca_programmes/sdd/events/Rio20/Workshop-Institutional-StrategicFrameworks/MerseiEjiguSDIndicatorsFrameworkforAfrica.pdf	2011	UN	Draft version for discussion
Indicator Frameworks for Assessing Irrigation Sustainability		http://www.clw.csiro.au/publications/technical2005/tr1-05.pdf	2005	CSIRO – Australian Research Institute	1. Include sustainability indicators based on system elements, system attributes and on a range of spatial scales 2. Presents different indicator frameworks for selection (i.e. state and control, driving force state response, TIM, AMOEBA) 3. Assess criteria for framework selection and assess frameworks
Water policy and reform framework in Australia	http://www.environment.gov.au/water/australia/coag.html	** Most of the document links do not work in the main webpage		Australian government	1. Different documents of principles, guidelines, objectives for water quality management.

	National Water Quality Management Strategy http://www.environment.gov.au/water/publications/quality/index.html http://www.environment.gov.au/water/publications/environmental/index.html	http://www.environment.gov.au/water/publications/quality/pubs/water-quality-framework.pdf http://www.environment.gov.au/water/publications/action/pubs/cehw-framework.pdf	2002 2009		Some of them are more specific sub-frameworks with measures 2. Main topics: fresh and marine water, groundwater, diffuse and point sources, sewerage system, effluent management, water recycling 3. Water use prioritization framework, cooperative use
A National Framework for Improved Groundwater Management in Australia		http://www.environment.gov.au/water/publications/environmental/groundwater/pubs/framework-groundwater.pdf	1996	Australian government	Includes the main topics and indirectly presents indicators that should be defined for groundwater management
Conceptual Framework to Develop and Use Water Indicators		http://siteresources.worldbank.org/INTEEI/811099-1115809852605/20486439/ConceptualFrameworktoDevelopandUseWaterIndicators1999.pdf	1999	CIAT Colombia	Water indicators developed for two approaches: a project-based approach, and a Pressure-State-Impact-Response approach
Water framework directive (this is the framework for the whole EU)	http://www.water.org.uk/home/policy/water-framework-directive/about-wfd		2006 - 2010	UK	1. Webpage: aims, objective, strategy, timetable, milestones (However no specific pdfs of the framework itself)

	http://www.water.org.uk/home/policy/water-framework-directive http://www.doeni.gov.uk/niea/water-home/wfd.htm http://www.legislation.gov.uk/uksi/2003/3242/contents/made	http://www.water.org.uk/home/news/press-releases/sustainability-indicators-09-10/sustainability-2010-final.pdf http://www.doeni.gov.uk/niea/ams-report.pdf			2. Water sustainable indicator report for the UK
Swiss sustainable indicator system	http://www.bfs.admin.ch/bfs/portal/en/index/themen/21.html	http://inderscience.metapress.com/media/m3pnwhtyvral7xxuueet/contributions/x/k/0/5/xk0583543t853h57.pdf	2007	Switzerland	A paper that describes how the system was built, the development processes, selection of indicators and critical assessment
Minnesota Water Sustainability Framework	http://wrc.umn.edu/watersustainabilityframework/index.htm	http://wrc.umn.edu/prod/groups/cfans/@pub/@cfans/@wrc/documents/asset/cfans_asset_292471.pdf	2011	USA, University of Minnesota Water Resources center	Complete framework document, including environmental, social and economic components. Vision, objectives, Strategy, Outcomes, Measures of Success, and Benchmarks
Ecosystem Services Indicator Framework		http://www.esindicators.org/files/esid/Framework%20discussion%20for%20download.pdf			
Sacramento River Basin Report Card & Technical Report	http://ice.ucdavis.edu/waf/	http://ice.ucdavis.edu/waf/sites/ice.ucdavis.edu.waf/files/WHIP_TechRep_2010_0.pdf	2010	Sacramento River Watershed Program(SRWP)	Environmental Indicators for the Feather River Watershed

The State of the Great Central Valley of California Indicator Series	http://www.greatvalley.org/indicators/index.aspx	Multiple, see URL link	Ongoing, last in 2009	Great Valley Center	Economy, Environment, Community Well-Being, Public Health Access, and Education and Youth Preparedness.
State of the Sound	http://www.psp.wa.gov/	http://www.psp.wa.gov/downloads/SOS09/09-04534-000_State_of_the_Sound-1.pdf	2009	Puget Sound Partnership	Various ecological and human health indicators.
The Index of Sustainable Economic Welfare	http://www.econ-pol.unisi.it/dipartimento/it/node/296	http://www.econ-pol.unisi.it/quaderni/449.pdf	2005	Università degli Studi di Siena, Italy	Economic evaluation like "gross domestic product"
Health-e-Waterways	http://www.health-e-waterways.org/		2009	University of Queenslands	environmental indicators (watersheds)
Chesapeake EcoCheck	http://www.eco-check.org/		2011	NOAA	Mostly environmental (water quality) indicators
Delta Stewardship Council – Fifth Staff Draft Delta Plan			2011	Delta Stewardship Council	Water supply, water quality, and ecosystem condition measures

Related to the topic of sustainable water management but there were no detailed frameworks.

EUWARENESS - research project on European Water Regimes and the Notion of a Sustainable Status	http://www.euwareness.nl/home/	http://www.euwareness.nl/methodology/Applied%20methodology.pdf http://www.euwareness.nl/methodology/Scientific%20and%20socio-economic%20objectives.pdf http://www.euwareness.nl/summary/Background%20of%20the%20EUWARENESS-project.pdf		EU Commission University of Twente in the Netherlands.	1. Methodology and case studies 2. Scientific and social objectives

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B-Sustainable is a project of Sustainable Seattle	http://www.b-sustainable.org/about-the-b-sustainable-project	http://www.b-sustainable.org/about-the-indicators-framework	Started 1993, continuously updated	Sustainable Seattle	1. A webpage including the history, development and indicators for natural, built, social, personal environment goals

Appendix D Candidate Sustainability Indicators

The following table lists 120 sustainability indicators corresponding to each of the 7 sustainability goals. To select indicators, 42 sustainability indicator systems (Appendix C) containing over 1,800 indicators were reviewed for their potential use in the California Water Sustainability Indicators Framework. These are not the final indicators possible for any given water sustainability assessment, others may be preferable or possible.

Table 1. Proposed goals and indicators

California Water Sustainability Indicators Framework		
Water Sustainability Goal	**Water Sustainability Indicator**	**Other Relevant Goals for Indicator**
Goal 1: Sustainable Water Management: Manage and make decisions about water in a way that integrates water availability, environmental conditions, and community well-being for future generations.		
	Greenhouse Gas Emissions	
	Historical Drought Severity (WRI)	
	Storm Resilience	
	Aquifer Declines	2
	Baseline Water Stress (WRI)	2
	Drought Resilience	2
	Energy Requirements for Water Delivery	2
	Groundwater Stress (WRI)	2
	Water Demand	2
	Water Risk (WRI)	2
	Benefits from Water Management	3
	Completion of Stewardship Actions	5
	Inter-annual Variability (WRI)	5
	Flood Resilience	6

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	Historical Flooding Occurrence (WRI)	6
	Equitable Decision-Making Process	7
	Participation in Local Stewardship	7
	Water Travel Distance	2,3
	Water Scarcity Index	2,5
	Water Stress Index	2,5
	Sustainable Water Usage	2,7
	Potentially Unhealthy Water Supply	3,4
Goal 2: Improve Water Supply Reliability: Improve water supply reliability to meet human needs, reduce energy demand, and restore and maintain aquatic ecosystems and processes.		
	Affordable Water Prices	
	Available Water (WRI)	
	Earthquake Resilience	
	Residential Water Use & Conservation	
	Return Flows (WRI)	
	Upstream Storage (WRI)	
	Water Re-use	
	Water Shortage	
	Water Storage and Use	
	Aquifer Declines	1
	Baseline Water Stress (WRI)	1
	Drought Resilience	1
	Energy Requirements for Water Delivery	1
	Groundwater Stress (WRI)	1
	Water Demand	1
	Water Risk (WRI)	1
	Delta: Percent Water Supplied	3
	Delta: Water Usage	3

	Protected Aquifer Recharge Areas	3
	Non-potable Water Needs for Agriculture	4
	Percent Recycled Water	4
	Forest Land Conversion	5
	Public support and awareness of water system protection	7
	Water Travel Distance	1,3
	Water Scarcity Index	1,5
	Water Stress Index	1,5
	Sustainable Water Usage	1,7
	Upstream Protected Lands (WRI)	4,5
	Managed Geomorphic Flows	5,6
Goal 3: Contribute to Social and Ecological Benefits from Water Management: Improve beneficial uses and reduce impacts associated with water management.		
	Delta: Agricultural Improvements	
	Delta: Dependent Industrial Production	
	Delta: Fishing	
	Delta: Recreational Use	
	Delta: Recycled Water Usage	
	Jobs and Water Transfers	
	Land Subsidence	
	Water Transfer Benefits to Local Economies	
	Water Transfer Costs and Benefits	
	Benefits from Water Management	1
	Delta: Water Usage	1
	Delta: Percent Water Supplied	2
	Protected Aquifer Recharge Areas	2
	Equitable Access to Clean Water	4
	Groundwater: CalEnviroScreen	4

	Abundance of Key Native Species	5
	Coastal Economy: Commercial use rate of fish populations (MLPA)	5
	Coastal Economy: Recreation use rate of specific areas	5
	Flows for Fish	5
	Index of Biotic Integrity	5
	Mercury in Fish Tissue	5
	Native Fish Community	5
	Native Fish Habitat and Flow	5
	Riparian Habitat	5
	Trophic State Index	5
	Water Recycling and Stream Flow	5
	Support of Environmental Measures and Regulation	7
	Water Travel Distance	1,2
	Potentially Unhealthy Water Supply	1,4
	Abundance of Key Non-Native Species	4,5
	California Stream Condition Index	4,5
	Flow Patterns	5,6
Goal 4: Increase Quality of Water: Improve quality of drinking water, irrigation water, and in-stream flows to protect human and environmental health.		
	Delta: Water Quality and Irrigated Lands	
	Groundwater Nitrate	
	Groundwater Water Quality Index	
	Impervious Surface: Water Quality Index	
	Water Treatment Cost	
	Non-potable Water Needs for Agriculture	2
	Percent Recycled Water	2
	Equitable Access to Clean Water	3
	Groundwater: CalEnviroScreen	3

	Amount of Industrial Pollutants Released	5
	Fertilizer Application Rate	5
	Periphyton Cover and Biomass	5
	Pollutant and Bacteria Index	5
	Potentially Unhealthy Water Supply	1,3
	Upstream Protected Lands (WRI)	2,5
	Abundance of Key Non-Native Species	3,5
	California Stream Condition Index	3,5
	Impervious Surface: Geomorphic Condition	5,6
Goal 5: Safeguard Environmental Health: Protect and enhance environmental conditions by improving watershed, floodplain, and aquatic condition and processes.		
	Aquatic Fragmentation	
	Coastal Biodiversity: Species diversity and richness (MLPA)	
	Conservation and Restoration Projects	
	Preservation of Natural Habitats	
	Species Richness	
	Threats to Amphibians (WRI)	
	Unnatural Fire Regimes	
	Coastal Habitat: Biogenic habitat, extent and structure of macroalgal/plant communities (MLPA)	
	Coastal Fauna: Focal invertebrate species (sea urchin, sea star, abalone), density and size (MLPA)	
	Coastal Fauna: Predatory (piscivorous) fish, density and size (MLPA)	
	Coastal Fauna: Planktivorous fish, density and size (MLPA)	
	Coastal Fauna: Predatory (piscivorous) sea and shore birds, density and size (MLPA)	
	Coastal Processes: Zonation and change in zonation of intertidal species (SLR)	
	Coastal Fauna: Predatory benthic invertebrates (soft-bottom, MLPA)	
	Coastal Fauna: Predatory, demersal fish (soft-bottom, MLPA)	
	Coastal Fauna: Harbor seal abundance (MLPA)	
	Coastal Fauna: Suspension feeders abundance and size (MLPA)	

	Coastal Fauna: Abundance of larval, juvenile, YOY fish	
	Coastal Fauna: Surf zone fish assemblage (MLPA)	
	Coastal Fauna: Fledging rate of seabirds (MLPA)	
	Coastal Fauna: Recruitment rate of invertebrates	
	Coastal Fauna: Recruitment rate of fish	
	Completion of Stewardship Actions	1
	Inter-annual Variability (WRI)	1
	Forest Land Conversion	2
	Abundance of Key Native Species	3
	Coastal Economy: Commercial use rate of fish populations (MLPA)	3
	Coastal Economy: Recreation use rate of specific areas	3
	Flows for Fish	3
	Index of Biotic Integrity	3
	Mercury in Fish Tissue	3
	Native Fish Community	3
	Native Fish Habitat and Flow	3
	Riparian Habitat	3
	Trophic State Index	3
	Water Recycling and Stream Flow	3
	Amount of Industrial Pollutants Released	4
	Fertilizer Application Rate	4
	Periphyton Cover and Biomass	4
	Pollutant and Bacteria Index	4
	Channel Alteration	6
	Floodplain Restoration	6
	Stream Bank Stability	6
	Plant Growth Index	7
	Water Scarcity Index	1,2

	Water Stress Index	1,2
	Upstream Protected Lands (WRI)	2,4
	Managed Geomorphic Flows	2,6
	Abundance of Key Non-Native Species	3,4
	California Stream Condition Index	3,4
	Flow Patterns	3,6
	Impervious Surface: Geomorphic Condition	4,6
Goal 6: Integrate Flood Management Activities: Integrate flood risk management with other water and land management and restoration activities.		
	Flood Risk and Damage	
	Floodplain Protection	
	Hydrostatic Force on Levees	
	Levee Maintenance	
	Levee Stability	
	Levee System Integrity Index	
	Flood Resilience	1
	Historical Flooding Occurrence (WRI)	1
	Channel Alteration	5
	Floodplain Restoration	5
	Stream Bank Stability	5
	Managed Geomorphic Flows	2,5
	Flow Patterns	3,5
	Impervious Surface: Geomorphic Condition	4,5
Goal 7: Improve Adaptive Decision Making: Employ adaptive decision-making, especially in light of uncertainties, that support integrated regional water management and flood management systems.		
	Adaptive Management under Changing Conditions	
	Data Sharing and Distribution	
	Gravity Recovery and Climate Experiment (GRACE)	

	Public Water Information Reporting System	
	Representation of Local Jurisdictions	
	Standardize Data Collection and Reporting	
	Stream Monitoring	
	Workflow Processes	
	Communication of Uncertainty	
	Collaboration between Scientists and Policy Makers	
	Equitable Decision-Making Process	1
	Participation in Local Stewardship	1
	Public support and awareness of water system protection.	2
	Support of Environmental Measures and Regulation	3
	Plant Growth Index	5
	Sustainable Water Usage	1,2

Description of Candidate Indicators

The 120 indicator descriptions below are from Table 1 above, organized alphabetically. The indicators and their component metrics were drawn from existing indicator frameworks that deal with water management, water quality, watersheds, regional sustainability, and ecosystem health. It is a list of indicators so far, not all possible or even best indicators.

Indicator Name	**Short Definition/Summary**
Abundance of Key Native Species	Relative abundance trend of key indicator species at different life stages (i.e. Delta smelt, Longfin smelt, juvenile striped bass, Chinook salmon, all salmonid populations).
Abundance of Key Non-Native Species	Relative abundance trend of key non-native species, for example Brazilian waterweed (Egeria densa) and water hyacinth (Eichhornia crassipes), and harmful invasive species such as Microcystis aeruginosa and other harmful algal blooms (HAB).
Adaptive Management under Changing Conditions	Supports adaptation and resilience to climate change.
Affordable Water Prices	Percent of drinking water suppliers which have instituted an affordable "lifeline" rate for low-income residential customers.
Amount of Industrial Pollutants Released	Tons of industrial pollutants released and disposed of by watershed/region.
Aquatic Fragmentation	Aquatic fragmentation in a watershed or hydrologic region
Aquifer Declines	Number and estimated capacity of basins with years-long aquifer declines (known as overdraft) or projected future declines.
Available Water (WRI)	This metric describes the total water available from natural and managed flows and comes from the World Resources Institute (WRI). It is calculated as all water flowing into the catchment from upstream catchments plus any imports of water to the catchment minus upstream consumptive use, plus runoff in the catchment.
Baseline Water Stress (WRI)	Baseline water stress measures total annual water withdrawals (municipal, industrial, and agricultural) expressed as a percent of the total annual available flow. Higher values indicate more competition among users. This indicator was used by the World Resources Institute in the Aqueduct 2.0 project.
Benefits from Water Management	Equitable distribution of economic and health benefits from water management.
California Stream Condition Index	This is a biological index, composed of indicators & metrics representing the condition of the benthic invertebrate communities living in streams and rivers.
Channel Alteration	Artificial alteration of channel sides and/or bottom.

Coastal Biodiversity: Species diversity and richness (MLPA)	Diversity of species and functional groups and richness (number) of species are useful information for understanding ecosystem stability. Narrower measures of diversity, for example within one zone or ecosystem type or for one taxonomic group (e.g., birds) could provide more interpretable information than measuring the entire diversity of an area. Rocky intertidal areas are probably the most feasible place to collect data for this indicator, though this system type is also subject to dramatic natural and artificial disturbances.
Coastal Economy: Commercial use rate of fish populations (MLPA)	Commercial fishing contributes to local communities' economies. Metrics or this activity includes number of individual vessels, number of trips, and total landings per fish species (weight per species and size class). Other important information includes economic and social activity indirectly triggered by fishing in coastal communities. Focal species: nearshore rockfish, Dungeness crab, California halibut, and red sea urchin
Coastal Economy: Recreation use rate of specific areas	Recreational fishing contributes to local communities' economies. Metrics or this activity includes number of individual vessels, number of trips, number of clients, and total landings per fish species (weight per species and size class). Other important information includes economic and social activity indirectly triggered by fishing in coastal communities. Focal species: Rockfish, lingcod, and California halibut
Coastal Fauna: Abundance of larval, juvenile, YOY fish	Early life stages of fish species are more sensitive to disturbance than adult forms. They are also critically important to maintaining and increasing fish populations. These early stages may live in habitat types different from the adult forms and are thus subject to different natural and artificial pressures. Abundance of various early stages of individual species provides important information about those species, Diversity of early forms in a particular habitat type or location may point to the important nursery role of that habitat.

Coastal Fauna: Fledging rate of seabirds (MLPA)	Populations of annual breeding success of many seabirds fluctuates annually in response to prey availability and quality. Hence, seabirds are frequently used as indicators of food web changes in marine ecosystems. Cassin's auklet is a small diving seabird that feeds primarily on krill, mysids, and some larval fish. There is an existing historical record for this species, including average number of offspring per year from each breeding pair. The large-scale dispersal of this bird species means that range-wide and regional assessment of trend and condition can be made. Pigeon guillemots are found along rocky shores and in inshore waters. They dive and feed on sculpins, sand lance, and smelt. While nesting, pigeon guillemots are sensitive to local disturbance. Prey availability and nest disturbance may be reflected in breeding success for many seabirds (fledging rate). Focal species: Cassin's auklet, pigeon guillemot, Brandt's cormorant, pelagic cormorant, and common murre
Coastal Fauna: Focal invertebrate species (sea urchin, sea star, abalone), density and size (MLPA)	In marine and estuarine ecosystems, many invertebrates play key roles as herbivores, detritivores, and predators and are often termed "strong ecological interactors". Abundance of individual species can provide information about the ability of the ecosystem to capture and cycle nutrients and primary production to other trophic levels. Focal species for rocky systems: purple sea urchin, red sea urchin, red abalone, black abalone, giant/owl limpet, and various sea stars. Focal species for soft-bottom systems: Dungeness crab, sand crabs, razor clams, and sea stars.
Coastal Fauna: Harbor seal abundance (MLPA)	Harbor seals are an important apex predator, feeding on a diverse range of fish and invertebrates in nearshore waters including herrings, sardines, hake, flounder, sole, octopus, squid and crabs. Harbor seals spend about half of their time hauled out resting, sunning, reproduction, and interacting socially. Haul-outs can be in any coastal habitat and are locations suitable for assessing seal populations and role of local and regional disturbance in seal abundance.
Coastal Fauna: Planktivorous fish, density and size (MLPA)	Planktivorous fish (fish that eat plankton) abundance and size structure are indicative of the ability of the ecosystem to capture nutrients provided by the influx of plankton. These could be species that specialize in plankton, or juvenile stages of other species that eat plankton. Focus species: Blue rockfish

Coastal Fauna: Predatory (piscivorous) fish, density and size (MLPA)	The presence and increased abundance of predators indicates well-being in other trophic levels. Within kelp ecosystems, piscivorous fish may also play key ecological roles in moderating food web structure through top-down control. Certain fish are targeted by recreational and commercial anglers and well-being of populations of these species will provide social and economic benefits to coastal communities. Abundance and population structure (size classes) are important metrics for this indicator. Focal species include: Various rockfish, lingcod, cabezon, bocaccio, leopard shark, and bat ray
Coastal Fauna: Predatory (piscivorous) sea and shore birds, density and size (MLPA)	Resident and migratory birds forage in soft-sediment and rocky-intertidal ecosystems on a wide range of fish and invertebrate species. Populations of these birds can vary with climatic and oceanographic conditions as well as availability of prey in intertidal systems. Diversity of species and abundance of species are both important metrics. Focal species: black oystercatchers, Brandt's cormorant, pelagic cormorant, pigeon guillemot, and common murre
Coastal Fauna: Predatory benthic invertebrates (soft-bottom, MLPA)	As in many ecosystems, in soft-bottom habitats, predators may play an important role in structuring animal communities. The density and size structure of focal predator species can indicate health of other trophic levels. The benthic invertebrates referred to here are those with a strong association with the substrate and may be subject to fishing pressure. Focal species: Dungeness crab and sea star
Coastal Fauna: Predatory, demersal fish (soft-bottom, MLPA)	Predators can play an important role in structuring community composition within ecosystems. Abundance and size structure of a range of fish species can provide information about the health of multiple trophic levels. Demersal fish are those with a strong association with the substrate. Many of these species may be subject to strong fishing pressure. Focal species: California halibut, starry flounder, and sanddab
Coastal Fauna: Recruitment rate of fish	Fish species vary in their reproductive strategies, from live birthing (e.g., certain sharks) to targeted release of gametes (e.g., salmon). Most larval fish stages must feed by the time their yolk is depleted. Availability of prey, climatic/oceanographic conditions, predation, stranding, pollution, and various natural & artificial disturbance can affect larval stages and thus recruitment of young into the juvenile-adult population. Although recruitment rates will naturally vary, measuring trends in rate for individual or many species across years or decades will provide important information about coastal ecosystem health.

Coastal Fauna: Recruitment rate of invertebrates	Marine invertebrates vary in their reproductive strategies, from brooding until settlement to broadcast spawning of gametes and from direct developing (non-feeding) forms to long-lived larval stages. Regardless of strategy, recruitment rates into existing or new habitat can determine survival of a species and adaptation to new conditions. Recruitment can be measured as successful settling or juvenile stages into appropriate habitat for the juvenile and/or adult form.
Coastal Fauna: Surf zone fish assemblage (MLPA)	Near-shore shallow-water habitats are home to a range of fish species, including juveniles that seek refuge from predators in open water as well as resident species that forage in the surf zone on fish and invertebrate prey. Surfperch play a major link in trophic transfer in the near-shore: their diet consists of isopods, amphipods, copepods, molluscs, and polychaete worms. They in turn are prey for larger fish, such as kelp bass, California halibut, sturgeon, rockfish and salmon, as well as harbor seals and birds. Surfperch and surf smelt are both subject to fishing pressure and surfperch may be in decline in California. Focal species: Surfperch and surf smelt
Coastal Fauna: Suspension feeders abundance and size (MLPA)	Suspension feeders play an important role in ecosystems, converting phytoplankton to biomass and, as prey, providing energy available to higher trophic levels. Presence of sand crabs indicates a beach with sufficient nutrient inputs and size of the beach populations may be related to near-shore richness. Sand crab populations are generally robust and may vary with climatic and oceanographic conditions. Razor clams are one of the longest-lived organisms in the sandy intertidal so they may integrate ecosystem conditions over long time-frames. Focal species: sand crabs and razor clams
Coastal Habitat: Biogenic habitat, extent and structure of macroalgal/plant communities (MLPA)	In temperate marine ecosystems, loss of biogenic habitat (i.e., habitat formed by the growth and architecture of particular species) has contributed to declines in fish and invertebrate populations and loss of species diversity. In estuarine ecosystems, habitat provisioning by eelgrass (Zostero marina) is critical to maintaining the ecological roles played by these estuaries as nursery and foraging habitats. In rocky-bottom ecosystems, canopy-forming kelp species (Macrocystis pyrifera and Mereocystis leutkeana) are primary producers and provide habitat by serving as surface area for sessile organisms and refuges for young fish. Extent and structure (stem density and size structure) of these habitats are important metrics. These can cycle with environmental conditions and herbivore pressure.

Coastal Processes: Zonation and change in zonation of intertidal species (SLR)	In the presence of naturally varying tides and storm conditions, intertidal organisms occupy certain ranges, or zones, within intertidal areas. These zones vary in width and location depending on local topography and wave/tide reach. As sea levels change and storm conditions intensify with climate change, these zones will be altered in location, with some organisms occupying new territory and others potentially being excluded from certain areas due to lack of habitat. The intertidal monitoring program LIMPETS is tracking occupied zones over time, comparing their new records (collected by high school students) with records collected over the last 30+ years by Dr. John Pearse of UC Santa Cruz.
Collaboration between Scientists and Policy Makers	Collaboration between scientists and policy makers to understand data and communication needs.
Communication of Uncertainty	Communication of uncertainty, which can come from natural variation, measurement error, and incomplete knowledge of how systems function.
Completion of Stewardship Actions	The completion of restoration recommendations and key actions during the implementation phase of the process.
Conservation and Restoration Projects	Number of conservation and restoration projects.
Data Sharing and Distribution	Data sharing and distribution.
Delta: Agricultural Improvements	Investment in agricultural improvement for water management and quality in Delta region.
Delta: Dependent Industrial Production	Industrial production dependent on Delta water/region per year.
Delta: Fishing	Subsistence fishing use in the Delta.
Delta: Percent Water Supplied	Percentage of state and regional water supplied by the Delta.
Delta: Recreational Use	Trend in recreational use index in the Delta region.
Delta: Recycled Water Usage	Use of recycled water as a percent of total water used in the Delta region.
Delta: Water Quality and Irrigated Lands	Percentage of irrigated lands that meet water quality standards in Delta Region
Delta: Water Usage	Amount of Delta water used by sector (urban, agriculture, municipal, industrial) per season and per year
Drought Resilience	The maximum severity of drought during which core water demands can still be met, including social and environmental minimum requirements
Earthquake Resilience	The maximum earthquake intensity that can occur without causing more than some amount (e.g., $20 million) in damages due to water infrastructure disruptions, including levees
Energy Requirements for Water Delivery	Energy required per unit of clean drinking water delivered.
Equitable Access to Clean Water	Correlation between quality and quantity of available drinking water and household income.

Equitable Decision-Making Process	Equitable decision-making process for water management, diversity of participating organizations.
Fertilizer Application Rate	Rate of Fertilizer Applied (kg/ha)
Flood Resilience	The maximum flood that can be experienced without exceeding some amount (e.g., $10 million) in damages.
Flood Risk and Damage	Expected annualized damage for flood risk.
Floodplain Protection	Proportion of floodplain that is protected from development that is incompatible with flooding.
Floodplain Restoration	Extent of floodplain restoration and connection between channel and floodplain.
Flow Patterns	Flow pattern variability / alteration (both important seasonally and annually)
Flows for Fish	Sufficient flows and timing of flows for maintaining historically-present native fish.
Forest Land Conversion	Forest land conversion: Total acreage over time
Gravity Recovery and Climate Experiment (GRACE)	The Gravity Recovery and Climate Experiment (GRACE) uses a satellite-based method to estimate fluctuations in groundwater in the Earthâ€™s surface. By subtracting the water subcomponents soil moisture, snow-water-equivalent, and surface reservoir storage, the residual GRACE signal can be interpreted to represent basin-wide groundwater changes.
Greenhouse Gas Emissions	Greenhouse gas (GHG) emissions from land or water management, industrial/commercial activities, energy production, or transportation
Groundwater Nitrate	Groundwater describes water in soil and sub-soil substrates (e.g., aquifers) that is replenished across various time-frames by surface water that percolates to these underground reservoirs. For this water to be useable to meet human needs (e.g., drinking, irrigation) it must meet the same kinds of water quality requirements as surface water. One indicator of groundwater quality is nitrate concentration.
Groundwater Stress (WRI)	Groundwater stress measures the ratio of groundwater withdrawal relative to its recharge rate over a given aquifer. Values above one indicate where unsustainable groundwater consumption could affect groundwater availability and groundwater-dependent ecosystems. The indicator was used by the World Resources Institute (WRI) in the Aqueduct 2.0 project.
Groundwater Water Quality Index	Groundwater water quality index.

Groundwater: CalEnviroScreen	California Communities Environmental Health Screening Tool ("CalEnviroScreen") is intended to support assessments of the potential environmental pollution effects on communities, including disadvantaged communities, in order to support reduction in disparities and threats to health. The groundwater component of CalEnviroScreen provides a relative ranking of communities' groundwater condition and so should not be considered an absolute indication of health risk or cumulative effects.
Historical Drought Severity (WRI)	Drought severity measures the average length of droughts times the dryness of the droughts from 1901 to 2008. The indicator was used by the World Resources Institute in the Aqueduct 2.0 project.
Historical Flooding Occurrence (WRI)	Flood occurrence is the number of floods recorded from 1985 to 2011. The indicator was used by the World Resources Institute in the Aqueduct 2.0 project.
Hydrostatic Force on Levees	Cumulative hydrostatic force on levees and other flood-control structures
Impervious Surface: Geomorphic Condition	Proportion of watershed covered by impenetrable materials such as roads, parking lots, and buildings preventing water from leaching directly into the soil. The greater the proportion of watershed with impervious surfaces, the greater the likelihood of geomorphic processes and conditions being degraded due primarily to modifications of stormwater runoff dynamics.
Impervious Surface: Water Quality Index	Proportion of watershed covered by impenetrable materials such as roads, parking lots, and buildings preventing water from leaching directly into the soil. Water quality is affected by impervious surface development in watersheds. The more impervious surfaces are developed, the greater the chance that water quality will be degraded.
Index of Biotic Integrity	An index of biotic community composition and structure, which respond to disturbance
Inter-annual Variability (WRI)	Inter-annual variability measures the variation in water supply between years. This indicator was used by the World Resources Institute in the Aqueduct 2.0 project.
Jobs and Water Transfers	Job-equivalents per unit of water transferred from a source region (e.g., agricultural labor force).
Land Subsidence	Land Subsidence can be the result of depletion of aquifers. Both the absolute amount and rate of subsidence are used.
Levee Maintenance	Building standard and cost of maintaining levees/assessed value of the land use they protect.
Levee Stability	Frequency of levee breaks in the region.
Levee System Integrity Index	Levee system integrity index (stability, risk prevention, maintenance).

Managed Geomorphic Flows	Magnitude and timing of managed system flows suitable for native riparian habitats and geomorphic processes.
Mercury in Fish Tissue	Mercury in fish tissue is an important measure of water and sediment quality. for mercury to increase in concentration in fish tissue, it must be available in the environment (water and/or sediment) and methylated, usually by bacteria in hypoxic/anoxic conditions.
Native Fish Community	Ratio of observed to expected native fish species.
Native Fish Habitat and Flow	Sufficient and adequate direction of flows for maintaining historically-present native fish.
Non-potable Water Needs for Agriculture	Proportion of agricultural non-potable water needs--e.g. irrigation--met with non-potable water.
Participation in Local Stewardship	Participation rates in local stewardship by the local stakeholders such as municipalities, indigenous people, irrigation districts, community organizations, watershed associations, conservation groups, and stewardship groups.
Percent Recycled Water	Use of recycled water as a percent of total water used.
Periphyton Cover and Biomass	The amount and extent of cover of algae attached to the benthos and other underwater surfaces.
Periphyton Cover and Biomass	The amount and extent of cover of algae attached to the benthos and other underwater surfaces.
Plant Growth Index	This index reflects new plant growth in a gridded area, as measured by satellite/remote-sensing.
Pollutant and Bacteria Index	An index composed of indicators of chemical and bacterial pollution.
Potentially Unhealthy Water Supply	Number of people whose drinking water supply is potentially unhealthy.
Preservation of Natural Habitats	Acres of preservation of existing natural habitats and restoration of degraded habitats.
Protected Aquifer Recharge Areas	Number of acres protected or enhanced in aquifer recharge areas.
Public support and awareness of water system protection.	Public awareness and perceptions of the role water plays in their lives and in the environment can affect how people vote to support candidates, taxes/assessments, and bond issues. It is both important to keep the public informed to support democracy and to track their knowledge and perceptions in order to develop policies and management actions.
Public Water Information Reporting System	Public reporting system for data and results of analysis as well as methods used.
Representation of Local Jurisdictions	Process/data needs of local jurisdictions and geographies.
Residential Water Use & Conservation	Average water use /household, or /capita, 20% reduction by 2020 (per state law).

Return Flows (WRI)	Return flow ratio measures the percent of available water previously used and discharged upstream as wastewater. This indicator was used by the World Resources Institute in the Aqueduct 2.0 project.
Riparian Habitat	Naturally-occurring or artificial band of riparian vegetation along streams or rivers
Species Richness	Species richness (birds, fish, invertebrates), for example, the benthic macroinvertebrate community.
Standardize Data Collection and Reporting	Standardized methods for data collection and reporting and minimize collection biases
Storm Resilience	The maximum storm intensity that can occur without causing more than some amount (e.g., $10 million) in damages due to water infrastructure disruptions, including levees and floods
Stream Bank Stability	Stream bank stability.
Stream Monitoring	Proportion of streams monitored periodically for streamflow, temperature, fisheries, stability.
Support of Environmental Measures and Regulation	Level of support or opposition for environmental measures, such as statewide bonds and local environmental regulation (% of population).
Sustainable Water Usage	Annual withdrawal of ground and surface water as a percent of total annually renewable volume of freshwater.
Threats to Amphibians (WRI)	Threatened amphibians measure the percentage of amphibian species classified by IUCN as threatened. The World Resources Institute used this indicator in the Aqueduct 2.0 project.
Trophic State Index	Trophic state index is a measure of how eutrophic conditions are in a water-body. Excess algal growth can indicate eutrophic conditions and is the basis of the index.
Unnatural Fire Regimes	Ecosystems and species at serious risk from unnatural fire regimes.
Upstream Protected Lands (WRI)	Upstream protected land measures the percentage of total water supply that originates from protected ecosystems. Modified land use can affect the health of freshwater ecosystems and have severe downstream impacts on both water quality and quantity. The World Resources Institute used this indicator in the Aqueduct 2.0 project.
Upstream Storage (WRI)	Upstream storage measures the water storage capacity available upstream of a location relative to the total water supply at that location. The World Resources Institute used this indicator in the Aqueduct 2.0 project.
Water Demand	Total agricultural, residential, and commercial water demand, i.e. demand for all uses other than environmental needs and basic human drinking water requirements.
Water Recycling and Stream Flow	Increase measurable benefit in in-stream flows from water recycling and conservation.

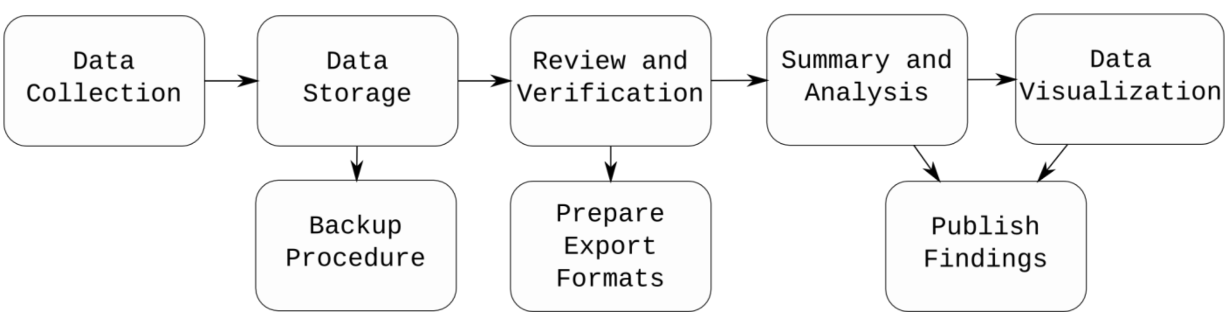
Water Re-use	Volume of water re-used (same volume can count more than once) as a fraction of total water used, including onsite, or recycled.
Water Risk (WRI)	Water Risk refers to the risk to water supplies from changes in climate and water withdrawals. The World Resources Institute used this indicator in the Aqueduct 2.0 project.
Water Risk (WRI)	Water Risk refers to the risk to water supplies from changes in climate and water withdrawals. The World Resources Institute used this indicator in the Aqueduct 2.0 project.
Water Scarcity Index	Water scarcity is a function of water availability and water use
Water Shortage	Percent likelihood per year, over the next 20 years, of water shortage.
Water Storage and Use	Years of average water use at current use levels represented by the current stored volume of water
Water Stress Index	Water stress index is typically defined as the relationship between total water use and water availability. The closer water use is to water supply, the more likely stress will occur in natural and human systems. This indicator has been used by the United Nations and others.
Water Transfer Benefits to Local Economies	Equitability of benefit realization for local economies in water-source and water-receiving regions due to water transfer.
Water Transfer Costs and Benefits	Fiscal cost and benefit for local economy in water-source region due to water transfer.
Water Travel Distance	Distance traveled for units of drinking and irrigation water.
Water Treatment Cost	Cost of water treatment.
Workflow Processes	Flow chart of process from data need, collection, analysis, decision-making, implementation, and results.

Appendix E Scientific Workflows

Scientific workflows offer both a theoretical as well as a practical way for building a comprehensive environment for data management, analysis, and decision support. Scientific workflows combine scientific data and process workflows, and provide a graphical interface to manage the pipeline of steps of a scientific problem (Ludäscher et al 2009). One can think of scientific workflows as similar to a flowchart, where the various nodes represent computational tasks and the lines connecting each step are the data inputs and outputs for each step. Each step can either be automated, such as a number crunching analytical task, or semi-automated, where external input and responses are required to complete the steps. A graphical interface allows for the chaining of the these tasks by managing the input and output of data between processes (Davidson et al, 2007).

Flowcharts are used in every industry to diagram process or business workflow. These illustrations are an excellent way of educating people about system processes, and they also provide excellent reference material for training and documentation. They can also be used to ensure certain steps are not omitted during a series of repetitive steps. While business workflows are based on business processes, scientific workflows are driven by data, and manage the data inputs, outputs, and transformations at various stages of the workflow (Bowers and Ludäscher, 2005). End-to-end data management practices can be incorporated into a scientific workflows, including data collection, storage, backup, retrieval, and analysis, and visualization. This explicit handling of the data management activities ensures that processes can easily be duplicated, and since it is a working workflow diagram, each step can also be well documented.

Scientific workflows provide an overview of the scientific problem broken down into its tasks and subtasks. From the data collection phase to data visualizations, a scientific workflow conveys these steps to the researcher so that each task in the process to each a completion of the scientific problem is well documented (Howe et al., .2009).



Scientific workflows offer a different way of looking at computation and data management. In a traditional model, the programmer schedules the execution of the control flow, and the system executes the specified procedures and functions. In scientific workflows, data transfer drives the computation. When the processes are connected to form a larger system, an executor initiates the workflow, and the flow of data initiates the pipeline of singular and parallel computational processes.

Scientific workflows, like social networks, are directed graphs where the nodes represent discrete computational components or process workflow steps and the edges represent results (data) which become the input parameters of the next node. Scientific workflows can be fully automated computational graphs, or semi-automated graphs with user inputs and human-based processes added (Ludäscher et al 2006).

Data Provenance in Scientific Workflows

A prominent feature to scientific workflows is how data provenance can be captured within the workflow. Data provenance refers to the origin of data, how it is managed, and how it is used for decision support. Scientific workflows explicitly provide these provenance pathways as edges in the directed graph. Each edge represents data flow, which have certain attributes and constraints that link the processes together. These dependencies define the provenance of data within the system, as they explicitly define the state of the data before they are consumed by the next step in the process (Davidson and Freire, 2008).

Data can undergo numerous transformations before it is stored in a database or data warehouse. Data lineage is the process of tracking the evolution of data, from the time of collection to the time of long term storage (Widom 2005). Data provenance documents how data was transformed so that reconstructing the original version of the data is possible. Data models need to include both provenance and lineage information so that researchers can query these metadata to understand the history of a data.

Scientific workflows can also be a good tool for documenting the lineage of the data, within the system. The data lineage includes where it comes from, what it is used for, and how it is transformed, at the various stages of the workflow. At any point in the process, it should be possible to recreate the exact state of the data.

Scientific workflows organize computational tasks, similar to a computer program, but they provide a user interface that allows researches--not just computer programmers--to understand better the scientific processes and data transformations used to solve the problem. The scientific method calls for a transparent handling of data and analysis so that the research community can replicate experimental results. Scientific workflow provides an excellent delivery mechanism of these results, where the visualization of the findings is joined with the methods performed to acquire data.

Building an Indicator Framework with Scientific Workflows

Each indicator within a framework has its own data management requirements. The data sources of often disparate, the techniques to transform and analyze the data are unique, and the visualization of these data depends on the environmental phenomenon being analyzed. Essentially, each indicator has its own scientific workflow.

While each indicator is different, they share many similarities. Each needs to collected data for analytical processing which leads to a result that allows managing stakeholders a means to make decisions. This often involves a visualization (graph), a summary of recent trends, or a comparison with other similar indicators. Therefore, once a scientific workflow is developed for an indicator, there is a strong possibility that the core structure of the workflow can be reused. Each workflow would essentially become a template for other indicators which perform similar tasks.

The ability to examine the data provenance within an indicator framework is critical. If decisions are made based on a particular analysis, having the ability to trace back to the data transformation can help verify those decisions. This can ensure a level of transparency in the decision making process, which is essential for indicators where grades or ratings are assigned to an environmental condition.

Scientific workflow processes can be integrated with online mapping components. The Open Geospatial Consortium (OGC) Web Feature Service (WFS) can be linked to workflow processes so that the generation of maps, an excellent visualization tool for the environmental sciences, can integrate into the workflow (Best et al. 2007).

There are several software applications to develop scientific workflows, including Kepler, VisTrails, and Taverna Workbench. Kepler and Taverna are written in the Java programming language, while VisTrails is written in Python. While building scientific workflows is still the task of a data modeler or programmers, some of these tools are making it easier for data analysts and project managers to participate in the workflows construction. There is a strong indication that these applications will continue to develop, perhaps to the point where such workflows can be modified over the web by decision makers, and provide specific tools for decision support.

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Appendix F Sustainability Indicators Reporting Framework

Introduction

Sustainability indicators provide easy-to-understand measures of the status and health of the environment, society, and economy. The status of parts of these systems can be presented as normalized values between 0 and 100, where higher values equate to a healthier, sustainable state. But while an indicator value can be easy to comprehend, the analytical methods, data management, and relationship between the raw parameters and the indicator framework is not as straightforward.

Proposed here is a reporting system to complement the indicators framework which would provide decision makers and interested citizens a view of the state of the environment and human systems through an easy to use interface. In addition, the reporting system would provide the essential provenance pathways so that the methods used to arrive at the indicator values can also be investigated and understood. This "drill down" ability would provide the sources of data used to calculate the indicator value as well as a description of the analytical methods used to calculate it.

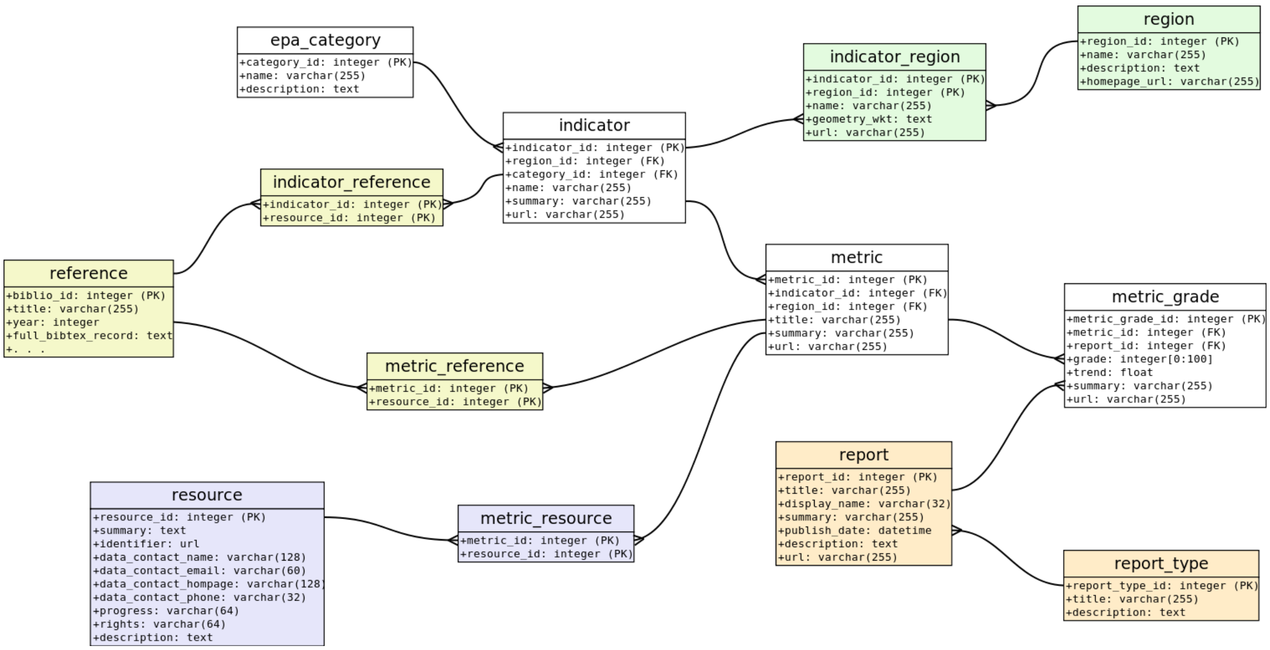
Architecture

The system would be a web-based information system, with both a relational and a spatial database back-end. While other tools could be used to build this system, a python-based web-application framework is proposed, with a PostgreSQL and PostGIS database back-end. Web mapping would be a core component of the system, where the spatial extent of the indicator value would be represented on a map, and would enable the user to navigate the map interface to view and retrieve other indicator values across space.

The indicator system would track all aspects of indicator development. It would contain a database of indicators from other projects so there is a link between California indicators and those used in other studies. It would link to the reports in which those indicators are used, so the decisions to build an indicator will have various authoritative sources. Therefore, the corresponding information about the data sources, the geography, the decision to choose one indicator over another, and a myriad of other connecting details should be part of this system. The development of the indicator can be just as important as the final result, or score, so all these details should be tracked within the system.

Indicators Data Model

The following data model shows the relationships for the proposed reporting system. Indicators are an abstract data type, and are at the core of the relational model. Indicators will have both properties and methods, although with this data model, only the properties are shown. This includes relationships with the goals and objectives of the indicator, the spatial extent (or regions) that the indicator is relevant, the analytical technique to generate the indicator value (internally called metric), the indicator report (reference) where the indicator is described, and the data resources used to calculate the value.



In building an online indicator system, there are many ways to approach the problem. The online system can be a simple reporting tool, or a more sophisticated decision support system (DSS). While the online DSS would take more effort to build, it would also provide more flexibility and allow the indicators to be manipulated online rather than external to the web application. It is possible to start with a simple reporting system, but it is advisable to design the application in a way that it could be expanded to a true DSS.

Static Indicator Management

Static indicator management is where a person must enter the results of the indicator analysis manually into web-based forms. The values get stored in the database, and are displayed at relevant times, such as on the regional indicator map, the indicator page, and in various reports. The analysis is external to the web application. The system is used to collect the results, but there are no mechanisms within the web application to change the underlying input values which generate the scores, and have the system update automatically. All the modification must be done by a data manager, and if the system becomes large, the data input requirements could be overwhelming.

Dynamic Indicator Management

A more sophisticated indicator management system enables the user to make changes to indicators online. A dynamic system becomes much closer to a true DSS as it would allow the user to combine indicators to create new indexes, adjust the distance-to-target values which would adjust the indicators score, and allow indicators to be recalculated automatically as new data is being added. The system would interface with the R statistical program in which certain indicator status and trend scores are generated. The system would require a data manager to setup new indicators, link to data sources, and build the necessary R programs to analyze the data (these steps are still necessary in a static model, but they are never linked to the indicator system). Once the system is setup, it would calculate the indicator scores automatically so the data entry requirements would be minimized.

Appendix G Ecosystem Services and Sustainability

There is a lot of overlap between sustainability indicators and measures of ecosystem services. To be sustainable, societies would recognize and protect services provided by natural systems that would be either impossible or expensive to replicate. Because of this, further discussion of measuring ecosystem services is provided below.

What ecosystem services are

Nature provides multiple benefits, also called ecosystem services, to humans. These include tangible services such as food and resources – fish, crops and freshwater, but also other less recognizable benefits including flood protection, erosion regulation, water purification and spiritual and cultural fulfillment. All these services, directly or indirectly, contribute to human well-being (MEA, 2005).

There are debates in the scientific literature about appropriate theoretical constructs to capture the essential attributes of ecosystem processes, services, and benefits (figure 5), while making sure the constructs are accessible and useful to land managers, land-owners, and agencies (Boyd and Banzhaf, 2007; Fisher and Turner, 2008). Superficially, some of this debate may seem about semantics (e.g., is pollination an ecosystem service, or is the food production from pollination the service?). However, as Wallace (2007) points out, terminology and logical and intuitive frameworks are keys to operationalizing the accounting for and protection of ecosystem services.

Ecosystem services can be quantified in their native units (e.g., tons C sequestered), and evaluated on the basis of their separation from the "ideal point" (Malczewski, 1999). Thus service/benefit values are re-scaled by comparing to a desired measurable condition, as implied by objectives for the system.

Ecosystem services/benefits outcomes can also be aggregated and incorporated into an overall assessment of categorized services/benefits for a geographic reporting area. This step is not essential to quantifying services, but helps in evaluating progress toward goals and objectives, or aggregate value of an area of the landscape. Additive forms are one aggregation process, but is not the only one and not appropriate when services/ benefits are not independent (Keeney and Raiffa, 1976; Zeleny, 1982). In this case, the less restrictive weak-difference independence condition is necessary for multiplicative and multi-linear functions (Butler et al., 1997 & 2001; Thurston, 2001).

Consideration of ecosystem services in the Framework will be substantially based upon approaches and uncertainties identified as critical by the Millenium Ecosystem Assessment (2005). These include relationships between process and rivers across scales, the relative linearity of changes in ecosystem function in response to drivers, market and non-market valuation methods for services that can link ecosystem processes to benefits to people, modeling changes in services across likely landscape-scale scenarios, incorporation of human behavior to improve quantitative modeling and decision-support, cross-scale linking between services and (who) benefits, and effective communication with non-technical decision-makers. The MEA has much in common with more detailed ecosystem service evaluations in agricultural systems and in the West (figure 1).

Market opportunities exist for ecosystem services, often described as "payment for ecosystem service" (PES). PES programs are negotiated contracts with landowners to maintain a certain level of environmental performance to maintain or enhance ecosystem services (examples: Forest Trends and Ecosystem Marketplace, 2008). Developing ecosystem indicators and metrics and tracking project impacts using those measures can make it easier to access any operating regional ecosystem markets and if ecosystem markets are available and if metrics were developed, then system for ecosystem measurement should be well-suited to ecosystem market use.

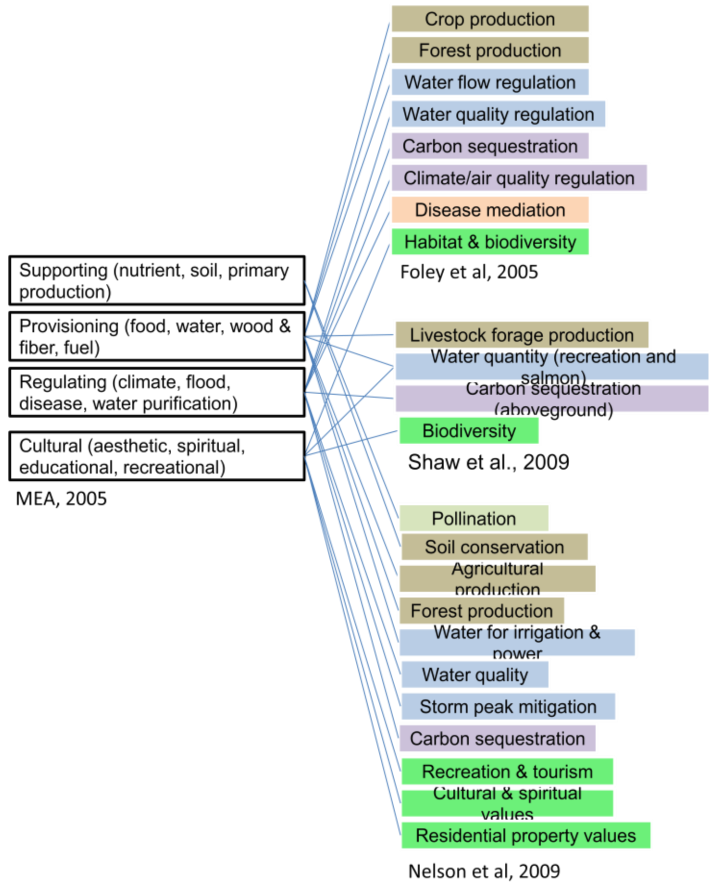


Figure 1. Cross-walk among the Millennium Ecosystem Assessment (2005) ecosystem services categories and those from 3 recent evaluations of ecosystem services in global agriculture (Foley et al., 2005), Oregon's Willamette Valley (Nelson et al., 2009), and California's rangelands (Shaw et al., 2009).

Ecosystem markets present various benefits for infrastructure agencies:

- First, it removes the risk of uncertainty of the project linked to the needed approval by environmental agencies. Projects are often slowed or stopped by deficient environmental analysis like the Environmental Impact Report (EIR) required by federal and state laws: National Environmental Policy Act (NEPA), California Environmental Quality Act (CEQA), or the Clean Water Act.
- Second, ecosystem markets include a transfer of liability: the liability for the restoration or conservation success is placed on the banker and not on the infrastructure agency.

- Third, this system produces a better alignment of mission since instead of water engineers, restoration professionals build the ecosystem service projects.
- Fourth, ecosystem market may produce improved ecosystem outcomes because bankers can have more comprehensive and meaningful projects to address ecosystem priorities.

But although PES systems have great potential power for ecosystem preservation, there are still major criticisms (Redford and Adams, 2009), including the risk that economic arguments about services valued by humans will overwrite and outweigh noneconomic justifications for conservation and the concern that there is no clear way to track the performance of the system. Therefore, ecosystem service markets must be only one of several tools aiming at preserving ecosystems.

All the major ecosystem services can be classified in four main categories according to the Economics of Ecosystems and Biodiversity (TEEB) system (Table 1):

a) **Provisioning services:** the goods and products obtained from ecosystems, which include crops, timber, and livestock as well as genetic resources for medicines.
b) **Regulating services:** the benefits obtained from an ecosystem's control of natural processes, in other words, from maintaining a healthy functioning ecosystem. These include water regulation and climate regulation.
c) **Supporting services:** the natural processes that maintain other ecosystem services, including nutrient cycling, water cycling, primary productivity.
d) **Cultural services:** intangible and non-material benefits people derive from nature, such as spiritual and aesthetic benefits as well as recreation and tourism.

Why indicators of ecosystem services are necessary

The Millennium Ecosystem Assessment, a worldwide study of the state of the world´s ecosystems, reported that 60 percent of ecosystem services were impacted and emphasized the importance of evaluating ecosystem services and the need to monitor them to achieve sustainable development (MEA 2005, Carpenter et al. 2009). In order to reverse current trends of ecosystem degradation and to become more sustainable, it is an urgent priority to integrate ecosystem service considerations into mainstream economic planning and development policy at all scales. Ecosystem service indicators can be used as tools for communicating the value and condition of ecosystem services to policy-makers and help them integrate this information with social and economic indicators.

How ecosystem services are provided

Natural systems and their elements are highly interconnected. The water cycle represents a good example of how ecosystem structure and processes provide services and benefits to people (Wright and Johnson 2011). Water is found in diverse forms and locations (streams, atmosphere, groundwater), each having a specific structure defined by biotic and abiotic attributes. Various processes (precipitation) and external environmental drivers (climate, geology) act on this ecosystem structure and on its specific functions (infiltration) to make water available and to move through the system. This ecosystem functioning allows the flow of energy among biotic and abiotic elements and continuously provides ecosystem services. Humans derive benefits from the use of water through direct consumption, through its living resources or after enjoying aquatic recreation activities. Additionally, people also benefit indirectly from ecosystem processes including water flow regulation or water infiltration. However, humans also modify the condition of water, the landscape and the biodiversity found in natural systems, which has an effect on the ecosystem functions and the services associated with them. A negative impact on ecosystem services can lead to the promotion of management actions and responses, which could restore, maintain or enhance the structure, condition and function of the natural system and consequently the services that depend on them.

There are complex interactions which comprise ecosystem services (figure 1). The provision of ecosystem services involves complex dynamics and interactions among the different elements, processes and functions of the system. An ecosystem function can be associated to multiple services and the strength of these associations could vary depending on the system conditions and external influences. Figure 2 illustrates an example of these interactions related to sediment retention as an ecosystem function.

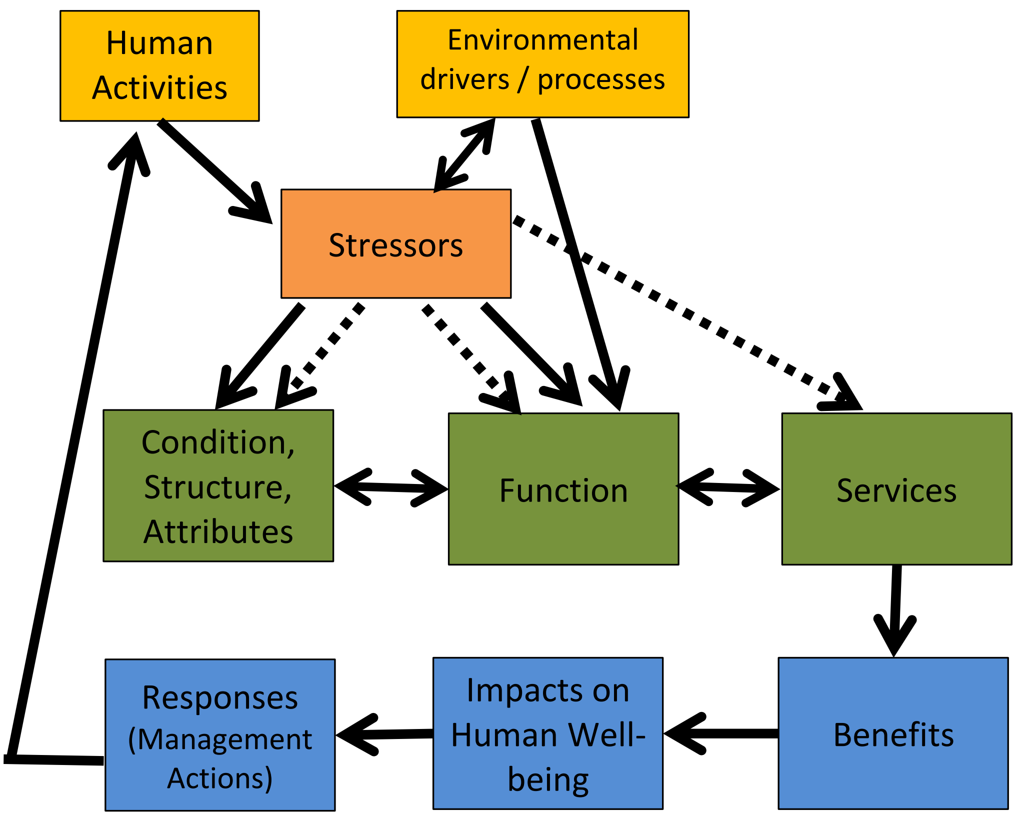


Figure 1. Model of ecosystem services provision (based on Wright and Johnson 2011, UNEP-WCMC & WRI 2009)

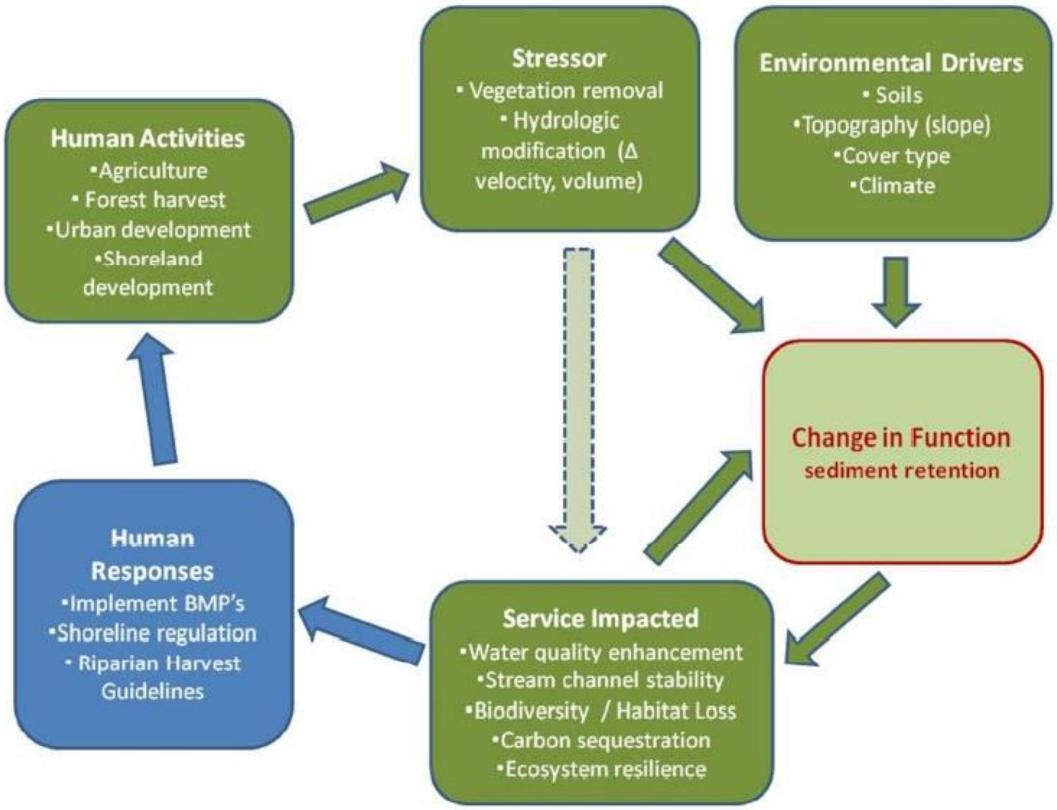


Figure 2. Sediment retention stressor-function-service-response diagram (Taken from Wright and Johnson 2011).

How to integrate indicators into an ecosystem service framework

The goal of ecosystem service indicators is to inform about the characteristics and trends in ecosystem services. Ideally, these indicators should provide information about the flow of service— the benefits people receive (Layke 2009). However, indicators of flow of service are not always easy to implement due the difficulty in measuring the flow of benefits from some regulating and cultural services (Feld et al. 2007). Therefore, in some cases it is necessary to rely on proxy indicators, which are substitute measures when it is not possible to measure the service directly. In the context of ecosystem services, examples include the amount of nutrient removed from agricultural runoff by wetlands (as a measure for nutrient retention and water regulation), and number of people visiting natural areas (as a measure for spiritual services).

A key first step in the development of an indicator system to assess ecosystem services is choosing the framework or conceptual model that the system will be based on. As flow of service - represented by the actual flow of benefits derived from the ecosystem service- is the goal to be monitored, frameworks including benefit models should be preferred (Layke 2009).

One example of this conceptual framework is the Benefits Model Building on the Ecosystem Services Framework (Balmfordet al.2008, figure 3). In this model, services directly enjoyed by people are identified as "benefits" while services that provide these benefits are termed "processes". In addition, benefits mostly include provisioning and cultural services while beneficial ecosystem processes include mostly regulating services (with water provisioning a notable exception). This example illustrates that there could be differences in interpretation and definition of the framework components when trying to measure benefits from ecosystem services. A conceptual framework for ecosystem services like the one included in Figure 1 differentiates between ecosystem processes, functions and services. However, when the objective is to operationalize the framework with indicators that are required to capture the flow of benefits derived from ecosystem services, the need to assess and clearly define these categories or components becomes more evident.

A team of experts working collaboratively on ecosystem service indicators since 2008 recommended a framework based on the following 5 components in order to identify flow of benefits and select indicators to measure them (UNEP WCMC& WRI 2009):

a) **Condition-Structure:** the ability of ecosystems to support ecosystem processes and deliver ecosystem services
b) **Function:** the processes by which ecosystems deliver services and benefits. Most regulating and supporting services can be ecosystem functions in this classification;
c) **Service:** ecosystem products that are important for supporting human well-being, but not directly consumed by people. For example, freshwater that is used for irrigation or aquaculture is classified as a service since the freshwater supports peoples' livelihoods but is not directly consumed;
d) **Benefit:** tangible products from ecosystems that humans directly consume. For example, fish produced by aquaculture would be classified as a benefit. Could be expressed in physical or value terms.
e) **Impact or Outcome:** indicators of the state of people's physical, economic, social, and spiritual well-being.

An example of the indicators proposed according to the UNEP- WCMC and WRI (2009) suggested framework is included in Table 2.

Current development of ecosystem services indicators

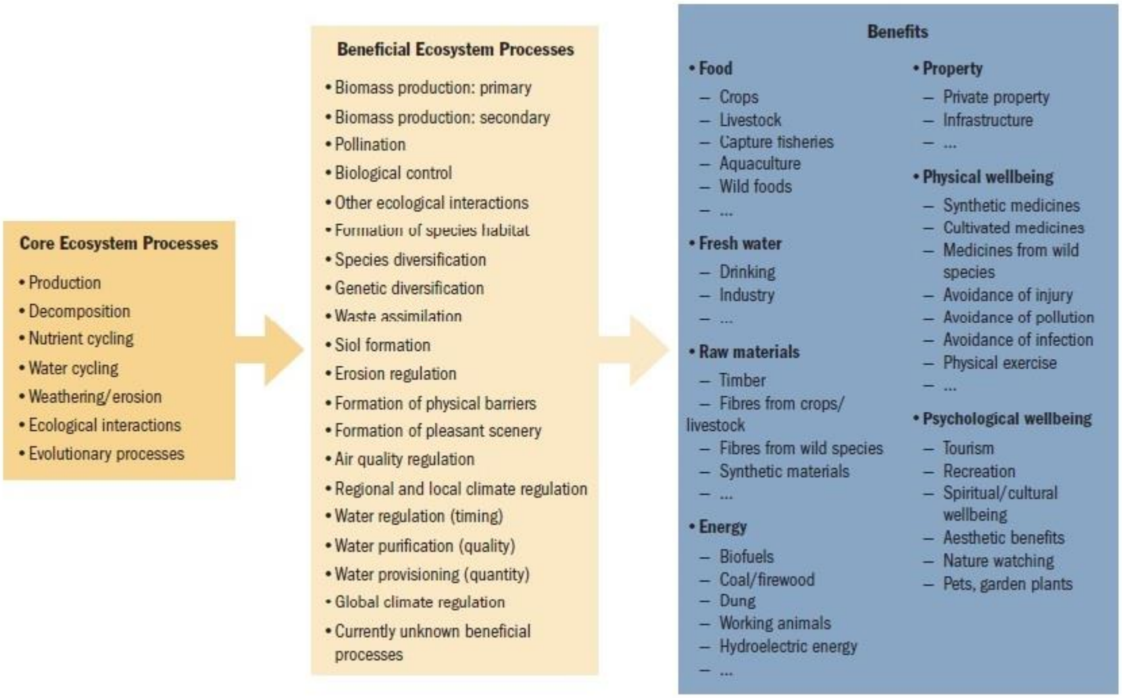
Ecosystem service indicators are relatively new tools to assess sustainable development. Frameworks, conceptual models and measures are being developed and evaluated for different topics, ecosystem elements and geographical areas. Two of the main issues that require further attention are finding the appropriate indicators that directly measure benefits flows and better understanding how indicators can adequately capture the interactions among system components and services. At the international level, there are currently efforts to develop and select indicators for ecosystem services and to compile an online ecosystem indicator database that can be used for policy-makers, resource managers and ecosystem assessment teams. The World Resources Institute (WRI) with the support of the UNEP World Conservation Monitoring Centre (UNP-WCMC) is leading these initiatives.

Table 1. The Economics of Ecosystems and Biodiversity (TEEB) classification of ecosystem services

Definition	**22 Service types**
Provisioning	1 – Food
	2 – Water
	3 – Raw Materials
	4 – Genetic resources
	5 – Medical resources
	6 – Ornamental resources
Regulating	7 – Air quality regulation
	8 – Climate regulation (including carbon sequestration)
	9 – Moderation of extreme events
	10 – Regulation of water flows
	11 – Waste treatment
	12 – Erosion prevention
	13 – Maintenance of soil fertility
	14 – Pollination
	15 – Biological control
Habitat/Supporting	16 – Maintenance of migratory species
	17 – Maintenance of genetic diversity
Cultural [provide opportunities for:]	18 – Aesthetic enjoyment
	19 – Recreation & tourism
	20 – Inspiration for culture, art, design
	21 – Spiritual experience
	22 – Cognitive development

Source: Groot et al. 2009

Figure 3. Benefits Model Building on the Ecosystem Services Framework



Source: Balmfordet et al. 2008

Table 2. Example of indicators proposed according to the UNEP WCMC and WRI (2009) suggested framework

	Condition	**Function**	**Service**	**Benefit**[1]	**Impact**
Supporting Services					
Gene pool protection	Number of livestock breeds Number and share of (OR: Population size / percentage) of (native) livestock breeds that are endangered Number of crop varieties	Hectares of land in traditional varieties: Number of breeding females / animals with each species		Number of resistant or tolerant livestock breeds or crop varieties	Avoided erosion of the genetic resource base Resistance to deceases
Regulating Services					
Climate regulation	Carbon stock (vegetation, soil, water bodies)	(Sustainable) net carbon storage/Net Carbon storage (Tc/time unit); Net sequestration net balance between ecosystems carbon gains and losses, also size of stocks in vegetation, soil and water bodies.			Avoided economic damage, body harm, livelihood damage, etc. as a result of climate change mitigation

[1] expressed in physical or value terms
Source: UNEP WCMC & WRI 2009

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Appendix H Ecological and Water Footprint

In Phase II of the Sustainability Indicators project, an estimate and trend of California's water footprint was developed. The water footprint is composed of water use/impact indicators and is thus an index of water impact. Because of its potential role in the Sustainability Indicators Framework, a more detailed description of how footprints work is provided below.

An ecological footprint is a measure of the impact humans have on the earth. In the simplest terms, it is a measure of resource consumption and waste production compared with the planet's natural ability to generate new resources and absorb waste. An example of just one facet of an ecological footprint is the use of trees for construction or paper production. The use of trees not only results in extraction of wood/pulp in the form of logging of forests, energy use, and land use change, but also in the production of waste in the form of landfill pollution.

According to the Global Footprint Network, humanity's ecological footprint is greater than twice the size it was in 1966. With a footprint this large, societies on earth require more than 1.5 planets to support life as we know it. Furthermore, the earth's ability to regenerate the amount of material humanity uses in a year takes 50% longer than the time it takes to consume the same resources. It is projected that in 2030 our need for resources will equal two planet Earths to maintain our current rate of consumption. Although there are global estimates for humanity's overall ecological footprint, countries differ in their contributions, measured in terms of consumption and biological capacity (the ability to regenerate natural attributes). Under the ecological footprint system, the combination of consumption and biological capacity results in either an "ecological credit" or an "ecological debt" measure for each country. Most countries in the world are currently operating as ecological debtors, using more resources than can be replaced in the same amount of time (Global Footprint Network 2010). In fact, while humanity's demands have been rapidly increasing, many countries are outsourcing resources (World Wildlife Fund 2010).

The Water Footprint Network developed a global water footprint standard that contains definitions and calculation methods for determining water footprints for different purposes and scales. The assessment contains four steps: Setting goals and scope, water footprint accounting, water footprint sustainability assessment, and water footprint response formulation. There are different types of water footprints: the water footprint of a product, consumer, community, national consumption, business, and any geographic area. The level of detail needed for data as well as the frequency of measurements depends on the spatial scale assessed.

Without understanding the level of input vs. outputs in our water cycle, we cannot grasp if, as a society, we are prepared for future population growth and the needs of humanity. The WWF estimates that although 1.8 billion people in the world have access to internet, 1 billion still do not have access to freshwater (World Wildlife Fund 2010). It is important to link water use to indicators that are both internal to a region (e.g. agriculture, consumed goods, energy, and land use) as well as external (e.g. imported products and services that use water outside the region either directly or indirectly). The indicator framework provides indicators that will help California measure its water footprint and ecological footprint. Measurements of ecological integrity, flood risk, land use, pollution, recreation, groundwater, and cultural uses, in addition to water use and quality in both the short and long term all contribute to our overall understanding of the water footprint and by extension ecological footprint.